AD 740618

DISPERSIBLE TRANSMITTING ANTENNA
VLF/LF INVESTIGATION

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Continental Electronics Mfg. Co.

FOREWORD

The work covered in this report was accomplished by Continental Electronics Manufacturing Company, P. O. Box 17040, Dallas, TX under Contract F30602-71-C-0010, Job Order 65230000. The period of research extended from 9 February 1971 through 9 December 1971. The Rome Air Development Center project engineer who monitored the work was Mr. David A. Kocyba (COAL).

This technical report has been reviewed by the Office of Information (CI) and is releasable to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved.

Approved:

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ABSTRACT

The problem was the development of an antenna system no more than 100 feet high for the frequency range 27 to 60 kHz having a radiating efficiency of 0.2% with a design goal of 0.5%. The input power capability was to be 50 kW. A theoretical design was proposed with five support towers 100 feet high and a square area of 425 feet on a side. A model was constructed at a frequency scale of 6.66 to 1.0 for testing. The model achieved the 0.2% efficiency, but the major loss in the system was the tuning inductors. The inductor problem was studied and the conclusions was that inductors having more than 1500 ohms suffered unanticipated losses from circulating currents due to approaching self-resonance. This led to a reconfiguration of the original array to one having seven support towers in a hexagon 340 feet on a side. Measurements on the model indicated 0.350% efficiency with a predicted efficiency for the full size antenna of 0.673%. The modification reduced the voltage on the system to 45 kV for 50 kW and indicate that a design for 100 kW input power is feasible.

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SECTION I

INTRODUCTION

This program was for the purpose of studying the feasibility of an electrically short antenna which will provide a minimum radiated power of 100 watts in the frequency range from 27 to 60 kHz. The study produces data for the design of a dispersible antenna 100 feet high to be used in survivable low frequency communications systems.

The system and methods proposed develop the maximum bandwidth-efficiency product and thereby offer good bandwidth as well as efficiency. Based upon previous study work, a special configuration was offered which has been named PARAN (Perimeter current antenna). It is based upon the principle, that if the vertical radiating portion of the current can be made to flow in a sheet on the perimeter of the available site area, then the maximum bandwidth-efficiency product for the available site will be developed.

In addition, if this current is constant from the ground lev to the height of the antenna, then the maximum possible radiation resistance for a given height is developed. This is equivalent to having the effective ight of the antenna system equal to its physical height.

After conference with RADC at the initiation of the program, it was confirmed that the concept as proposed agreed with the intent of the RFQ and the program was started by maximizing sub-elements of the system and then constructing a model for confirmation of the design.

SECTION II

PROPOSED ANTENNA SYSTEM

In answer to the Rome Air Development Center Request for Proposal, a four-element antenna was selected which was shown theoretically to meet both the specification requirement and also the design goal requested. This antenna configuration, as developed by Continental Electronics, increases the radiation resistance and, consequently, the efficiency of antennas of equivalent size by two methods. One is the development of constant current over the antenna height which develops the maximum possible radiation resistance for a given height. The second is the use of the mutual resistance of multiple elements which multiplies the single element radiation resistance almost proportionally with the number of elements used.

The antenna which was proposed is shown in Figure 1. It was 100 feet high as required by the specifications and 425 feet square. Figure 2 shows how the constant current on the vertical portion of the antenna is achieved, as in a quarterwave resonant antenna, by using a loading coil which is effectively in series at the top of the tower, but is physically placed at ground level, using the tower as a transmission line. The element is effectively fed at the top between the tower and top hat terminals. Figure 3 shows this results in the maximum possible radiation resistance for a single antenna of a given height (Reference 1). For a height of 100 feet at 27 kHz (.99 electrical degrees) this maximum resistance is

$$R_s = 40\left(\frac{2\pi G}{360}\right)^2 \qquad (1)$$

$$R_s = .01195 \text{ ohms (self-resistance)} \qquad (2)$$

This radiation resistance is further improved by dividing the current flow equally between four in-phase elements. The mutual resistance between those elements is shown in Figure 4. Based upon the spacings between elements, the total radiation resistance is the sum of the self-resistance shown above and the three mutual resistances from Figure 4, at 27 kHz.

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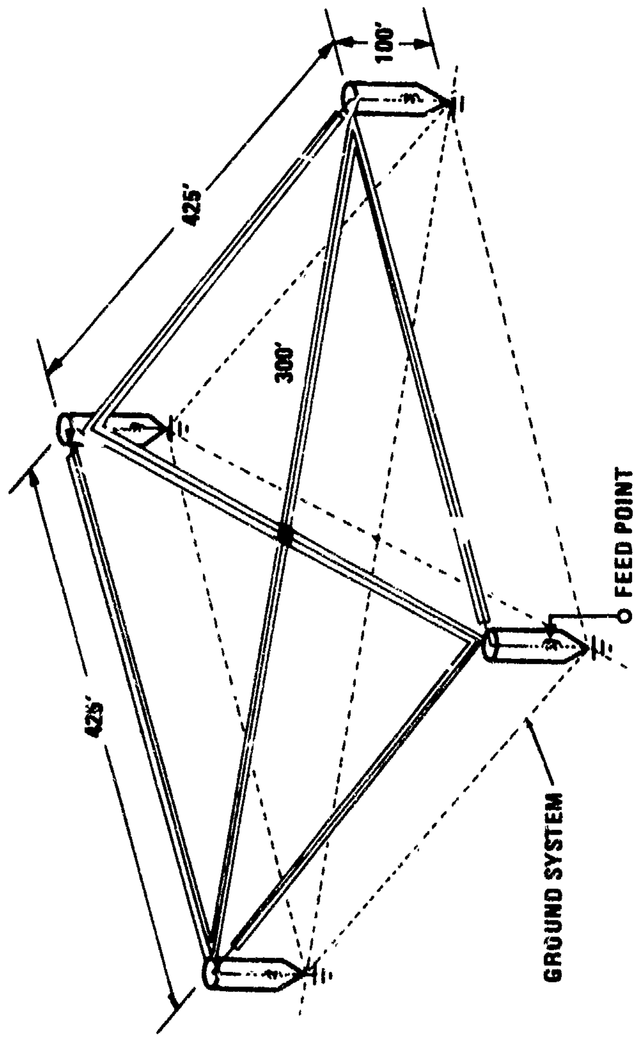

Figure 1. Proposed Antenna System

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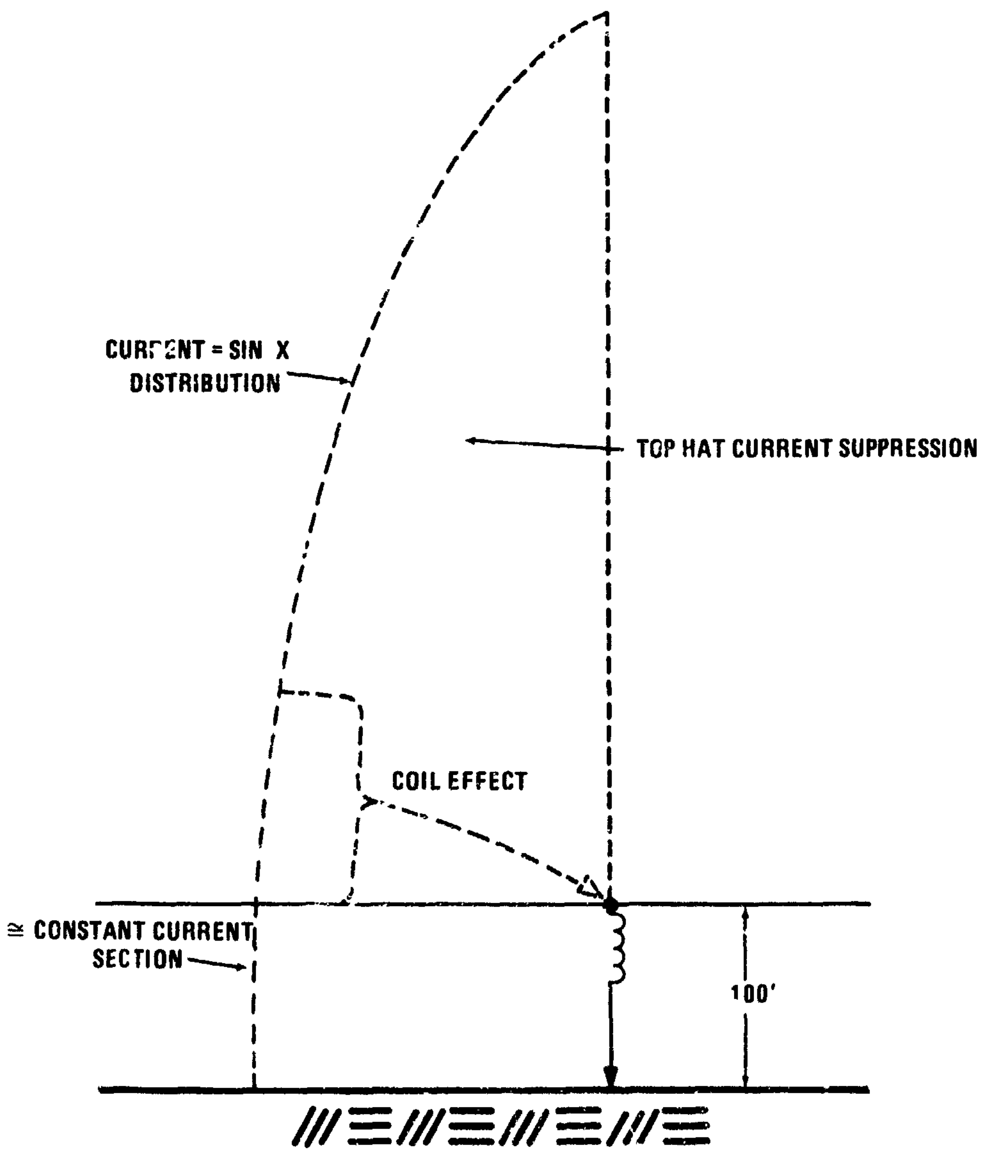

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Figure 2. Constant Current Top Loading

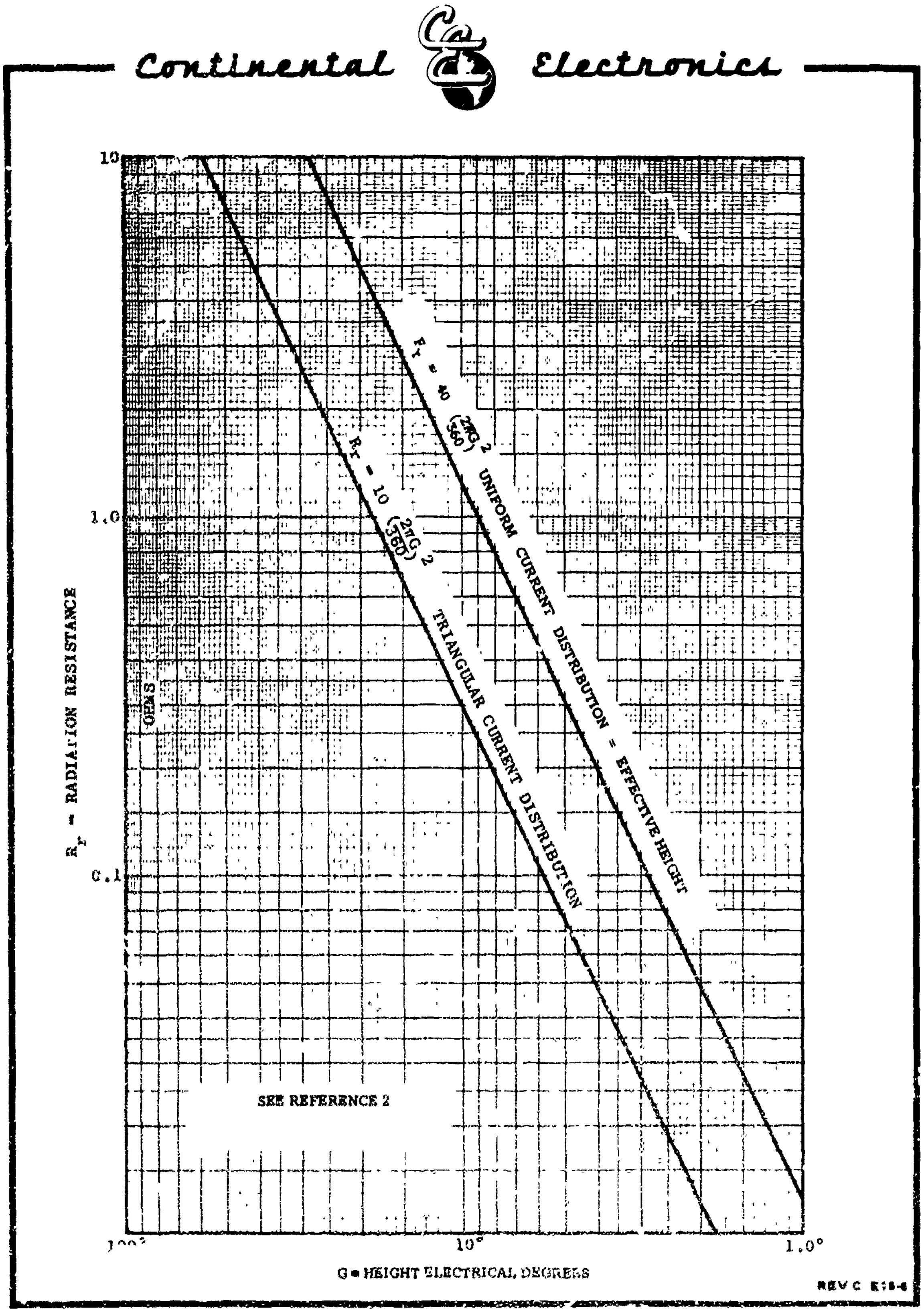
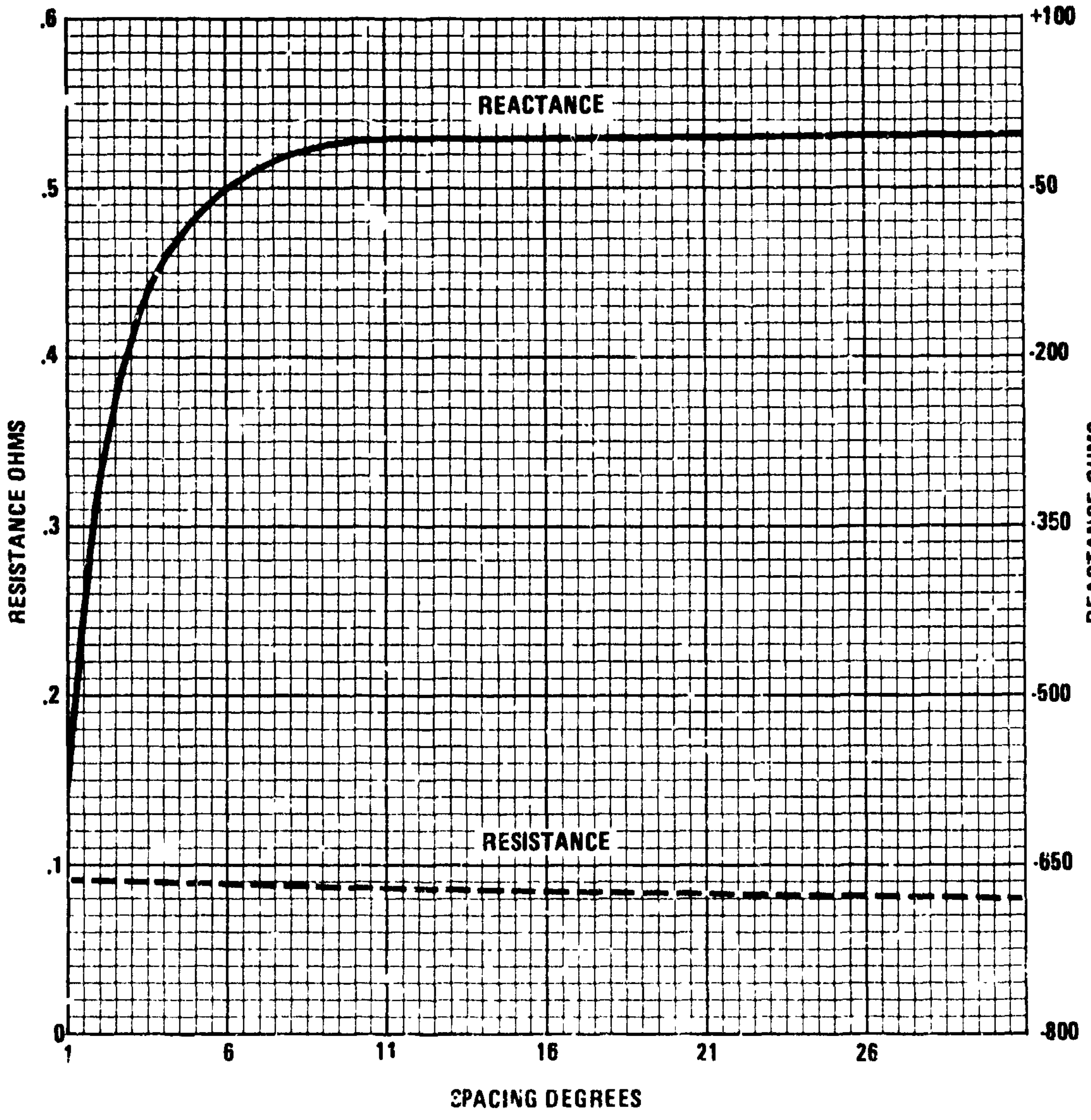


Figure 3. Radiation Resistance of Short Antennas



REV A F17-37

Figure 4. Typical Mutual Impedance Between Short Antennas

$$R_\alpha = .01195\ (1 + .992 + .992 + .995) \qquad (3)$$

$$R_\alpha = .0473 \text{ ohms} \qquad (4)$$

With an assumed ground and inductor loss of 3.6 ohms, and a reduction of radiation resistance due to physical sag in the top hat, the predicted efficiency of the proposed antenna was

$$\eta = \frac{.0473}{.0437 + 3.6} \qquad (5)$$

$$\eta = 1.2\% \qquad (6)$$

The specification calls for 0.2% with a design goal of 0.5% efficiency. With this margin for reduction to practice the work proceeded immediately by model work to maximizing the various parameters of the array.

SECTION III

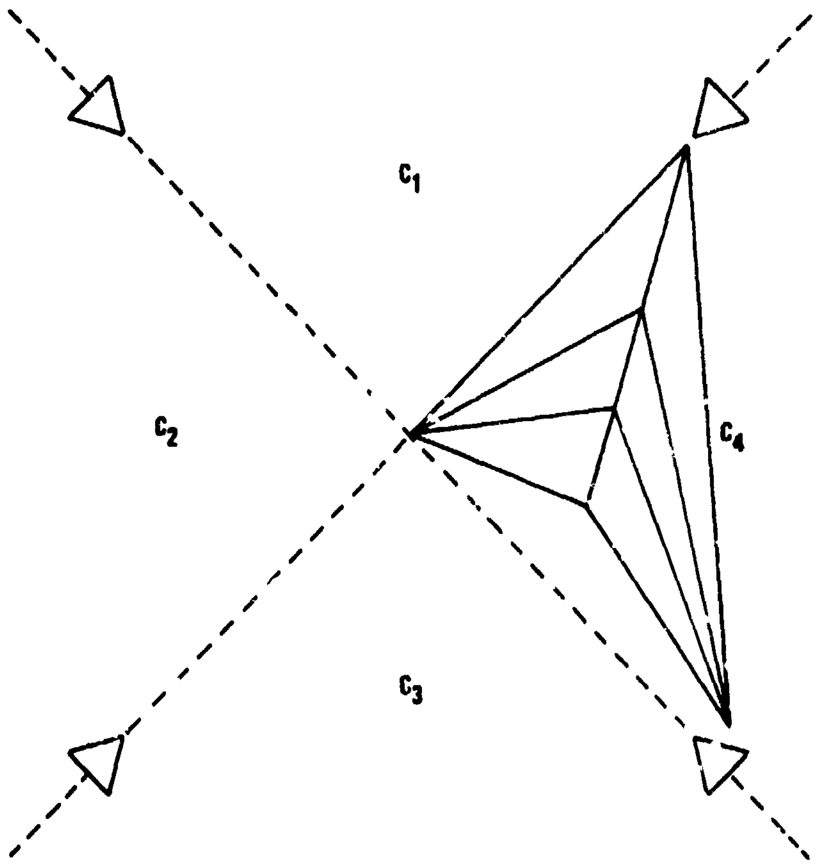
TOP LOADING STUDY

In this multiple-element antenna system, each element is separately tuned to resonance, and in so doing, the total top load capacity is divided equally between the elements. For a given configuration, the starting point is to develop the maximum capacity for each of the sub-divisions of the top hat.

In this way, the voltage and tuning inductor requirements are minimized. Figure 5 shows the position of the flat top allocated to each element in the proposed four-element system.

For this work, an aluminum ground plane system at a model scale of 1:120 was constructed and data was taken on various wire configurations. The best configuration for each number of wires is shown in Figures 6 through 11. The capacity for each was measured at dc and was also computed from the reactance measurements over the equivalent scale frequency from 3.25 to 7.2 MHz. A summary of the capacitance data is shown in Figure 12, and the reactance data in Figure 13.

The optimum number of wires for the flat top appeared to be three, four, or five, depending upon further analysis of corona and ground loss problems. The particular configuration for the elements was chosen to form as long a current path from the element tower to the common connection at the center of the array. This is to take advantage of the series inductance of the current path and thereby reduce the total reactance.



NOTE

Top View – C_1 - C_4 areas for developing top hat capacitance in 4 element model

X15-14

Figure 5. Top Loading Division Between Elements

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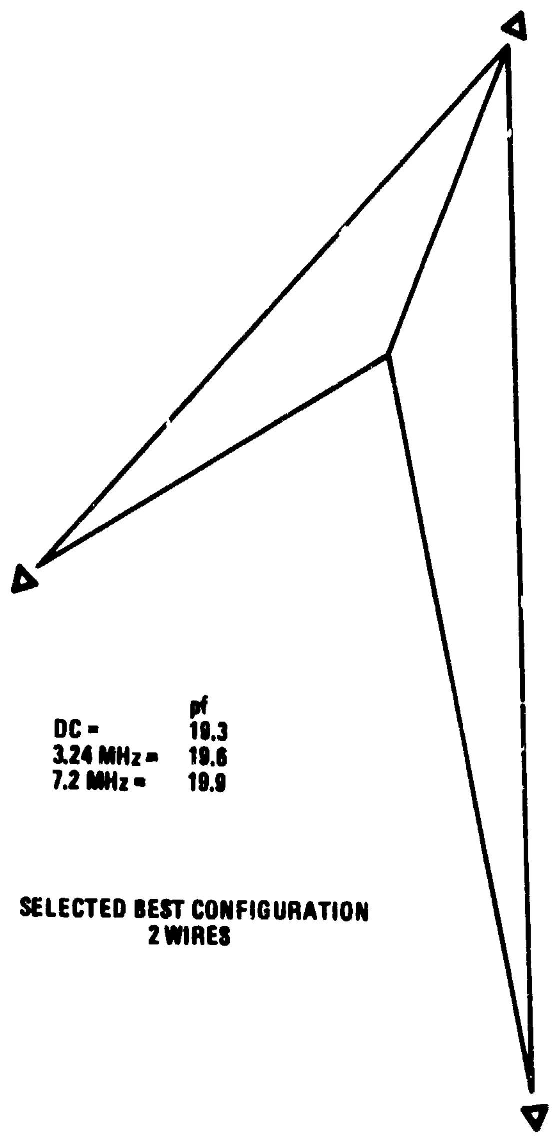

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Figure 7. Two Wire Top Loading

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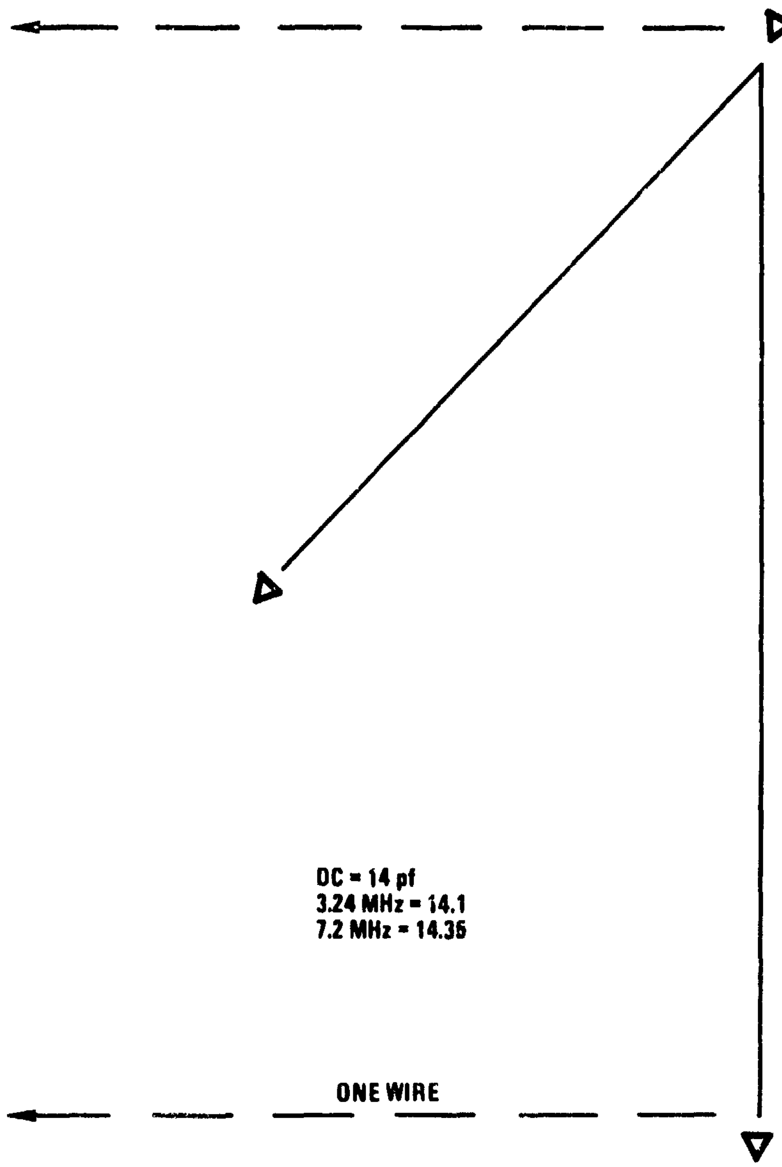

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Figure 6. Single Wire Top Loading

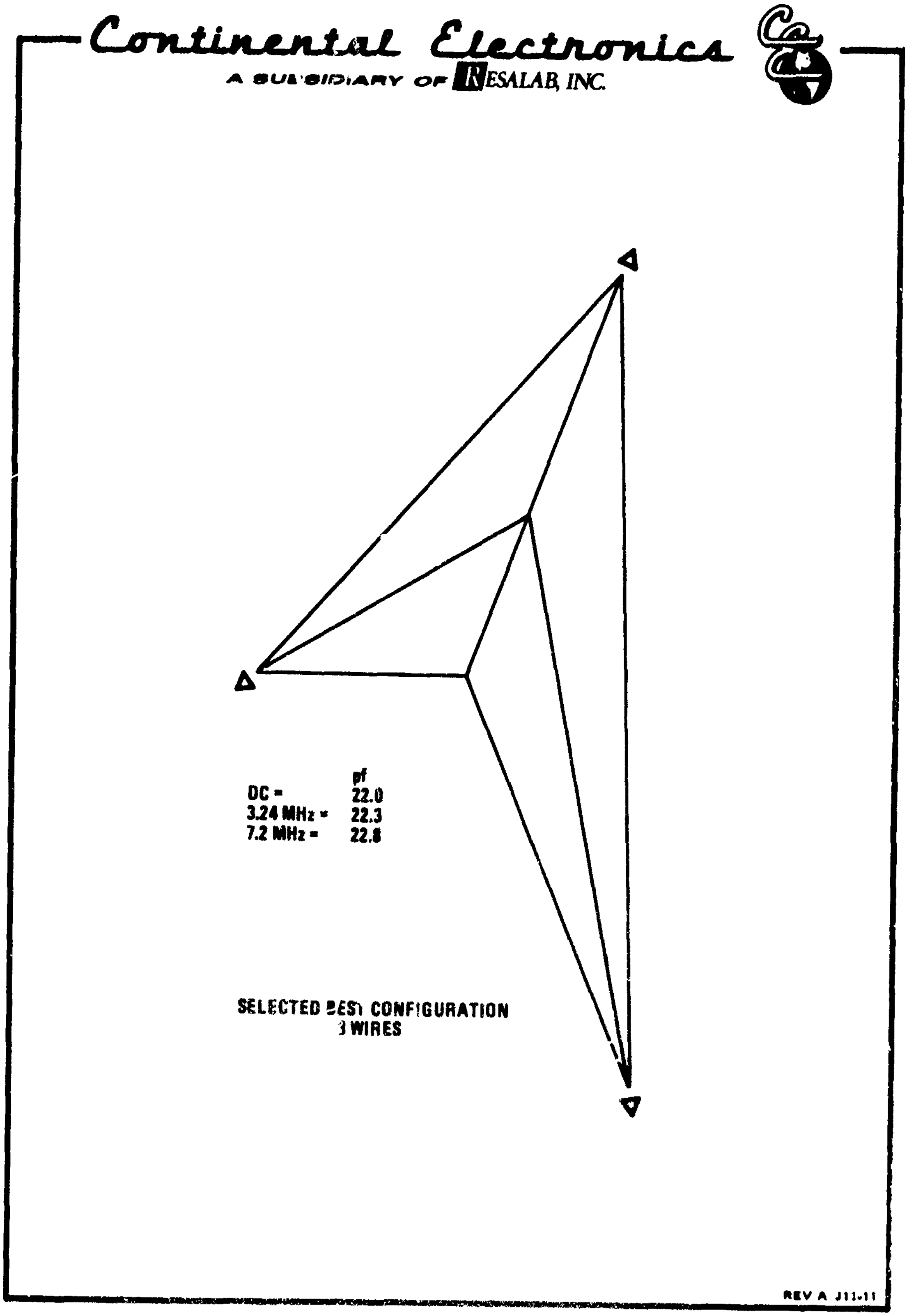

Figure 8. Three Wire Top Loading

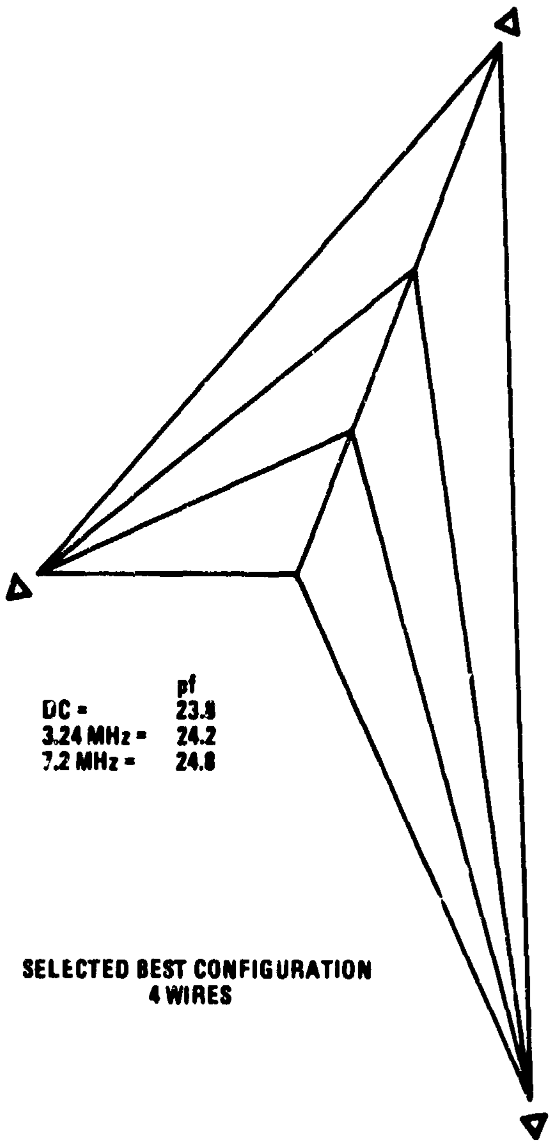

Figure 9. Four Wire Top Loading

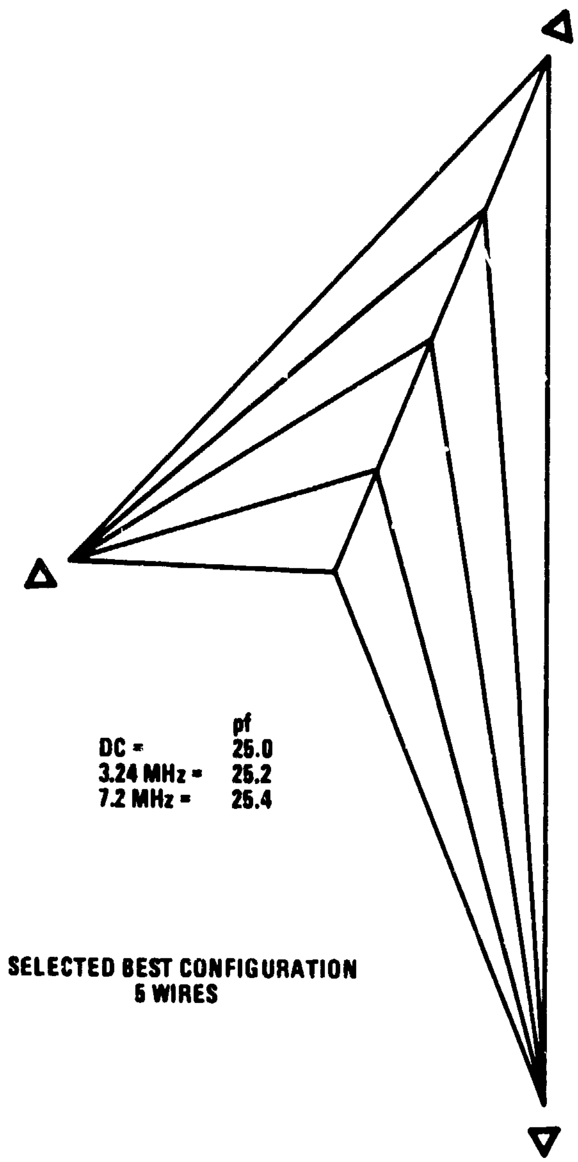

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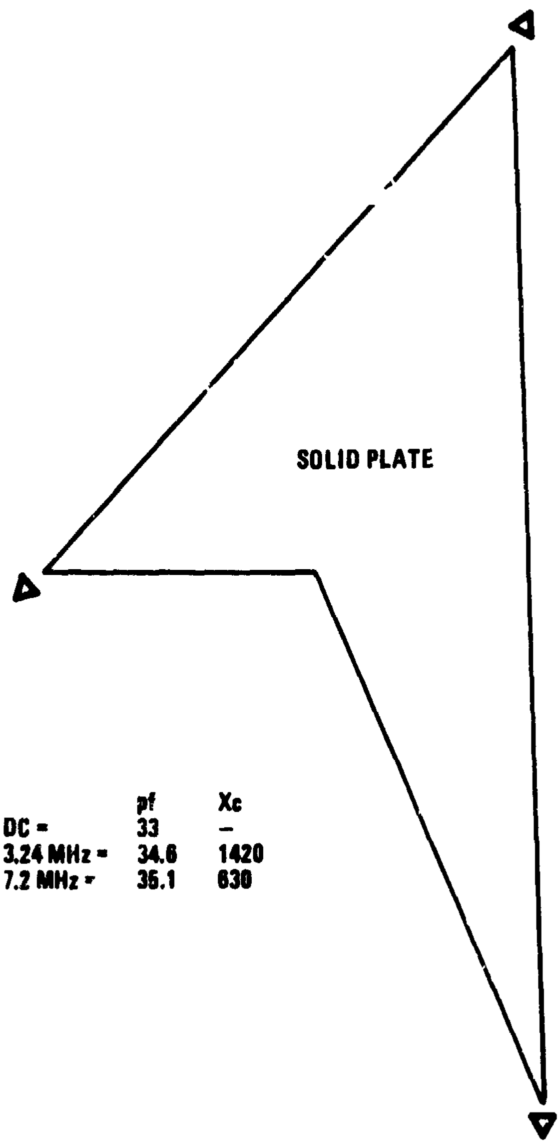
Figure 10. Five Wire Top Loading



	pf	Xc
DC =	33	–
3.24 MHz =	34.6	1420
7.2 MHz =	35.1	630

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Figure 11. Solid Plate Top Loading

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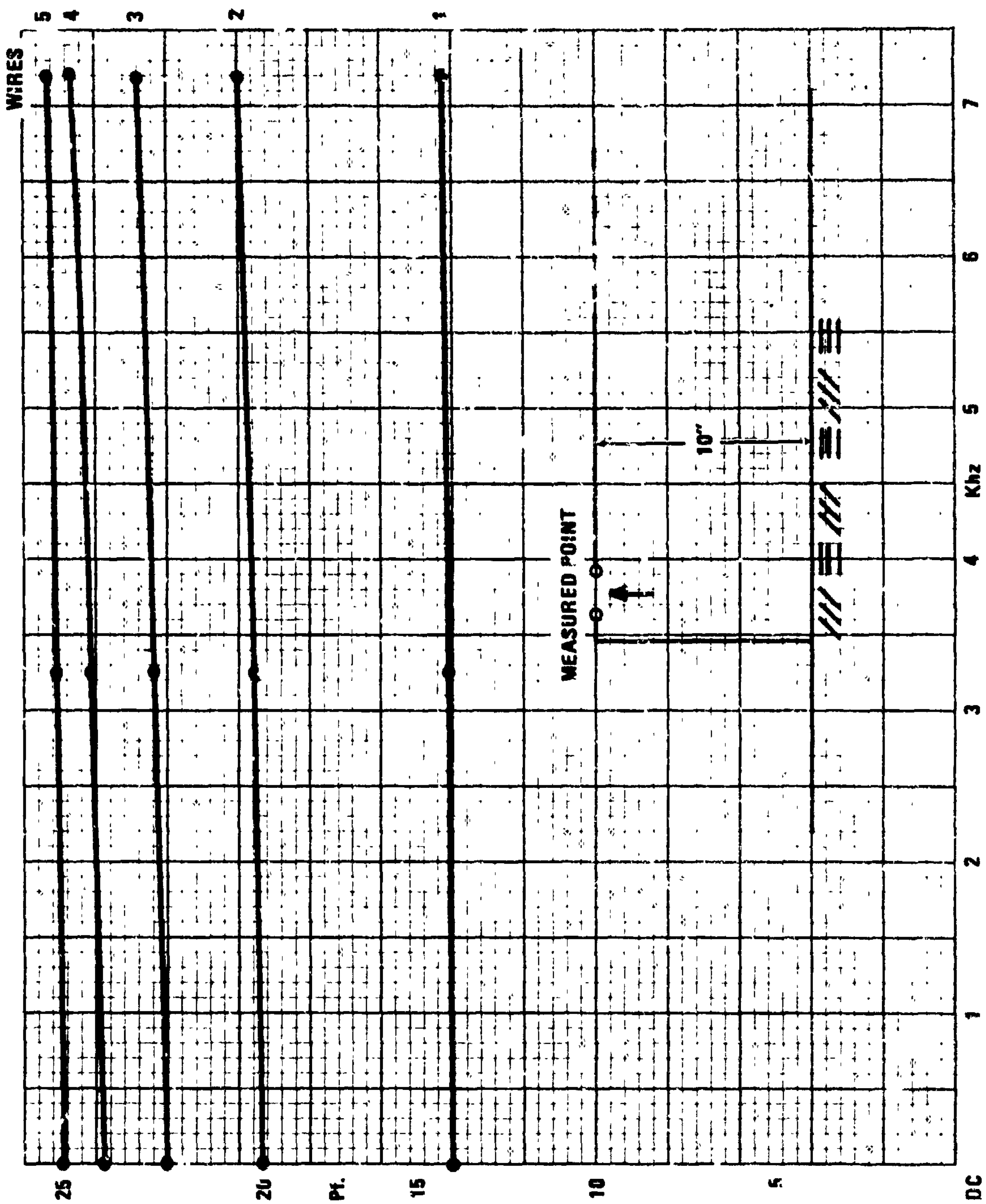

Figure 12. Input Capacitance. Single Element Model

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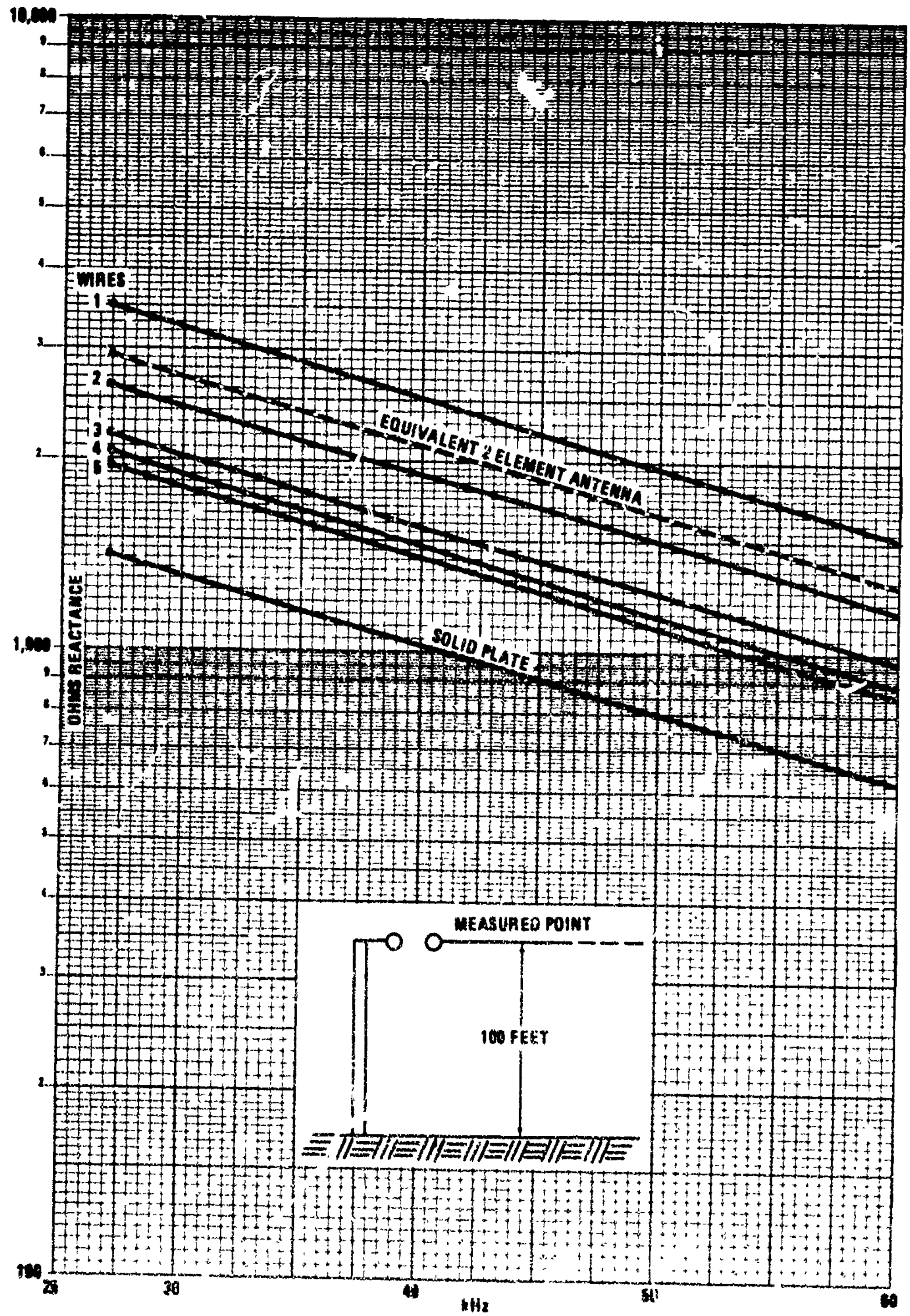

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Figure 13. Input Reactance, Single Element Model

SECTION IV

CORONA PREVENTION

The expected voltage potential on the top load portion of this antenna is directly related to the radiated power by elementary expressions. The design goal for radiated power is 250 watts. For a short monopole, this is a field intensity of

$$\varepsilon = F\sqrt{\frac{250}{1000}} \tag{7}$$

Where F is the known field intensity of a short monopole with 1000 watts of radiated power and is 186.3 MV/m at one mile distance. Therefore,

$$\varepsilon = 186.3\sqrt{\frac{250}{1000}} \tag{8}$$

$$\varepsilon = 93.15 \quad \text{MV/m} \tag{9}$$

The field intensity at one mile is related to the vertical current flow in any nondirectional antenna by

$$\varepsilon = 0.65A \tag{10}$$

where A is the area in ampere degrees under the function (Reference 2)

$$I = f(h) \tag{11}$$

Where f(h) is the vertical distribution of the total current flowing on the antenna. For this array, the current distribution is constant from its base to its top hat over an electrical length of 0.99° (100 feet at 27 kHz) so h = 0.99° and because it is constant

$$A = h \times I \tag{12}$$

From 10

$$\varepsilon = 0.65\ (h \times I) \tag{13}$$

$$I = \frac{\varepsilon}{.65h} = \frac{93.15}{.65 \times .99} \qquad (14)$$

$$I = 145 \text{ amperes} \qquad (15)$$

In a four-element antenna, this current is divided evenly between the four elements and each element has a current

$$I\varepsilon = {}^{145}/_{4} = 36.2 \text{ amperes} \qquad (16)$$

The approximate voltage on the top hat is due to the voltage drop across the tuning coil which from Figure 13 for four wires at 27 kHz has 2,060 ohms reactance. The voltage on the top hat then is

$$E = I \times X \qquad (17)$$

$$E = 36.2 \times 2060 \qquad (18)$$

$$E = 74.7 \text{ kV} \qquad (19)$$

A single wire 1/2 inch in diameter at 100 feet height above ground (200 feet to image) has a voltage gradient on its surface as shown in Figure 14.

$$G' = 0.57 \times 74.7 \qquad (20)$$

$$G' = 42.5 \text{ kV per inch} \qquad (21)$$

This gradient will be reduced with multiple wires in the top hat as shown in Figure 15. If we take a factor of 0.62 for adjacent wires and 0.8 for the second closest wire, the approximate gradient on 1/2-inch diameter wire in the configuration proposed is

$$G = 42.5 \times .62 \times .8 \qquad (22)$$

$$G = 21 \text{ kV per inch} \qquad (23)$$

The breakdown for dry air is 52 kV per inch giving a safety factor of 2. On this basis, 1/2-inch diameter top hat wire was selected for initial development work.

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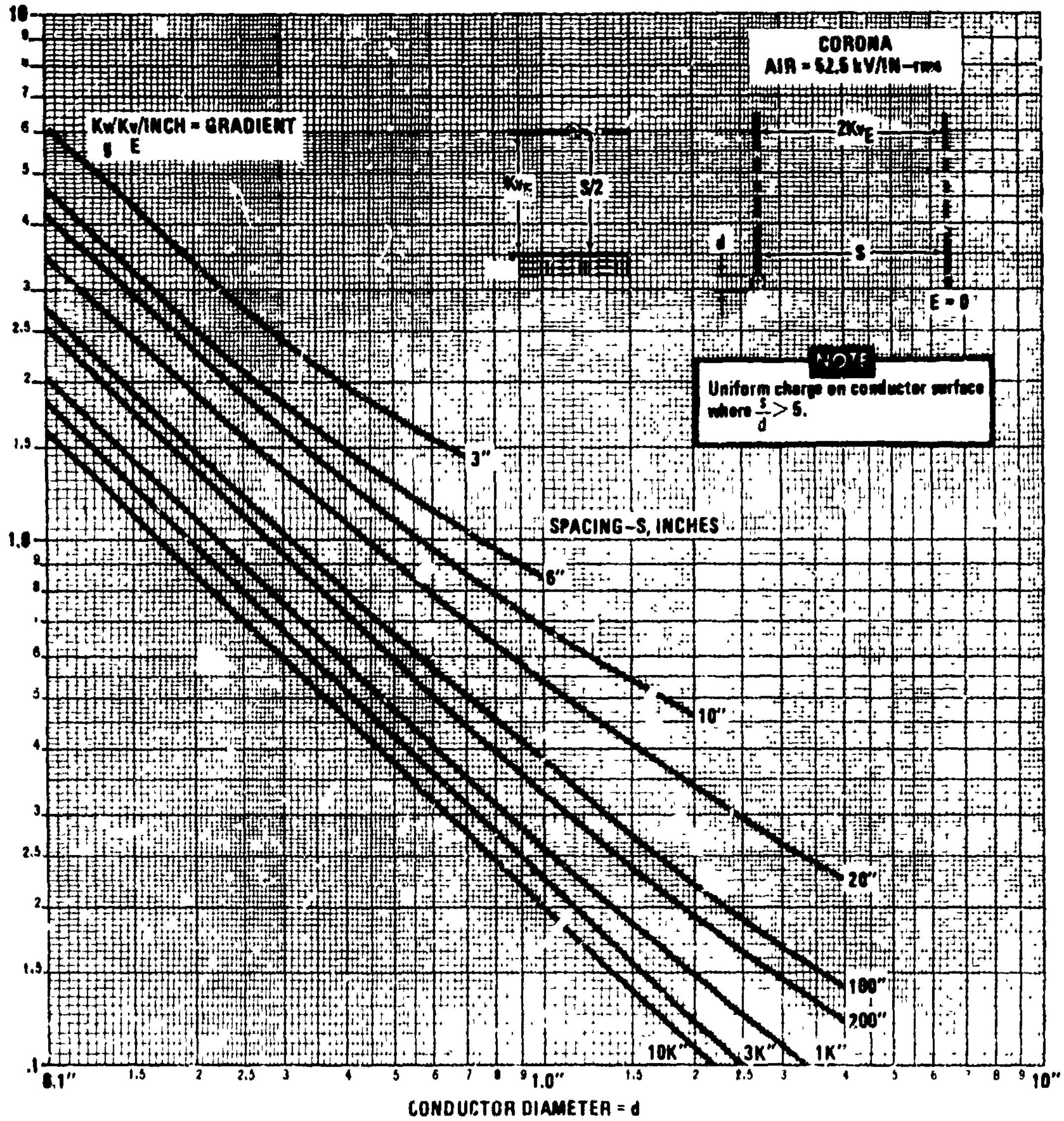

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Figure 14. Surface Voltage Gradient on Wires

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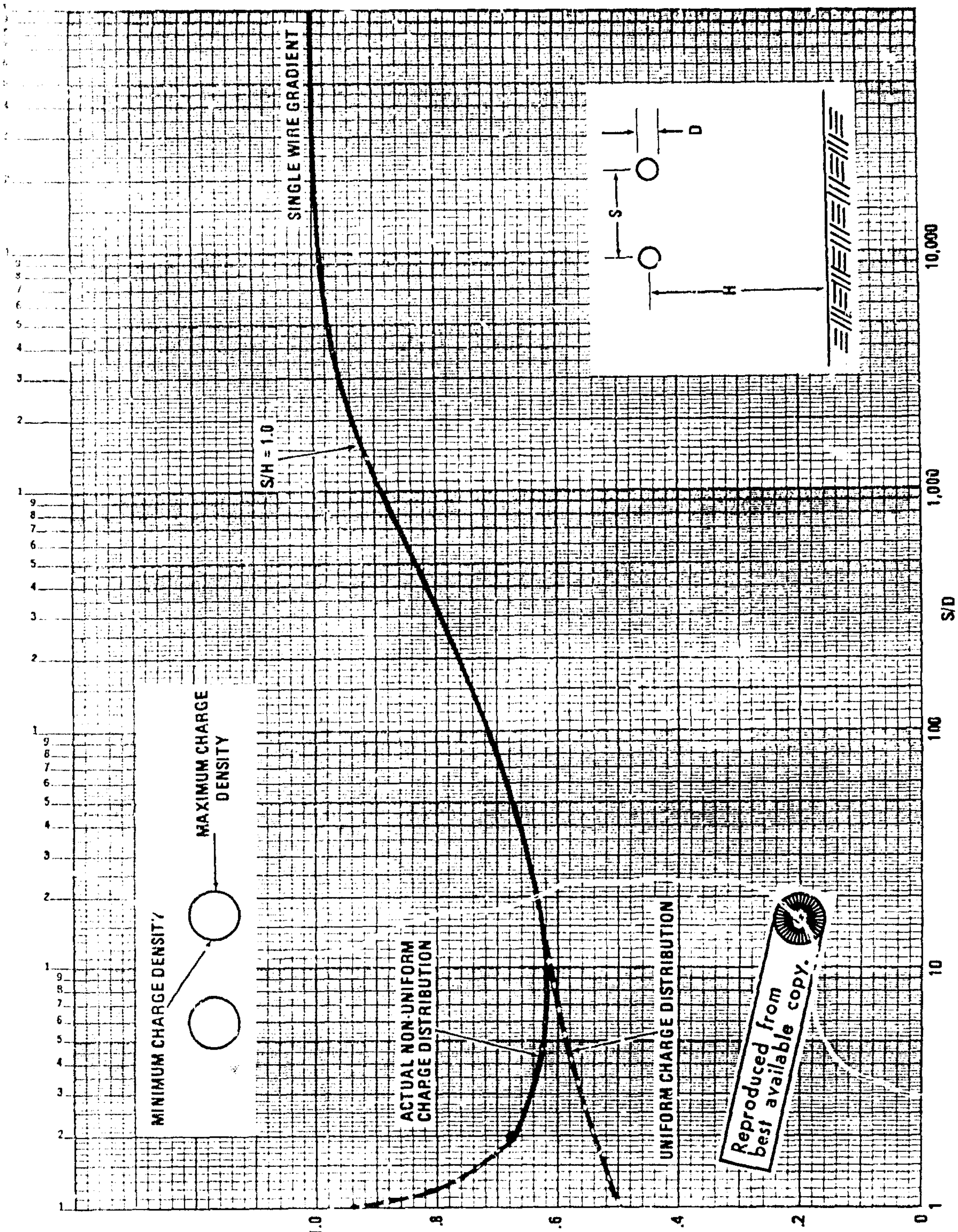

Figure 15. Two Wire Gradient Reduction

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SECTION V

GROUND SYSTEM

A more rigorous analysis has been made of the ground system requirements to determine the minimum system which will meet the efficiency requirements. This minimum system will ease the installation requirements and is the starting point for large scale model studies. Losses in the immediate vicinity of the antenna can be defined as the sum of E field and H field losses. These are best specified in terms of total watts per ampere of current at the tower connection to the ground system. This value then is in ohms and can be related directly to the radiation resistance at these same terminals for computation of the system efficiency and bandwidth.

The H field loss is due entirely to the radial current flowing in the ground from the base of the antenna caused by the current flow on the vertical portion of the antenna. The E field loss is due to that current which flows transversely or normal to the radial ground wires and is equal to the antenna displacement current immediately above the surface of the ground.

The total H field current flow is divided between the radial ground wires and the earth in proportion to their admittances. The characteristic admittance of soil is a complex number (Reference 1).

$$Y_S = \sqrt{\frac{\varepsilon - \frac{j\sigma}{\omega}}{\mu}} = (1 - j)\sqrt{\frac{\sigma}{4\pi f \mu}} \qquad (24)$$

ε dielectric constant

σ conductivity

f frequency

μ permeability

The values of Y_S for practical soil conductivities has been calculated and is shown in Figure 16. Abbott has also shown that the admittance of a parallel grid is

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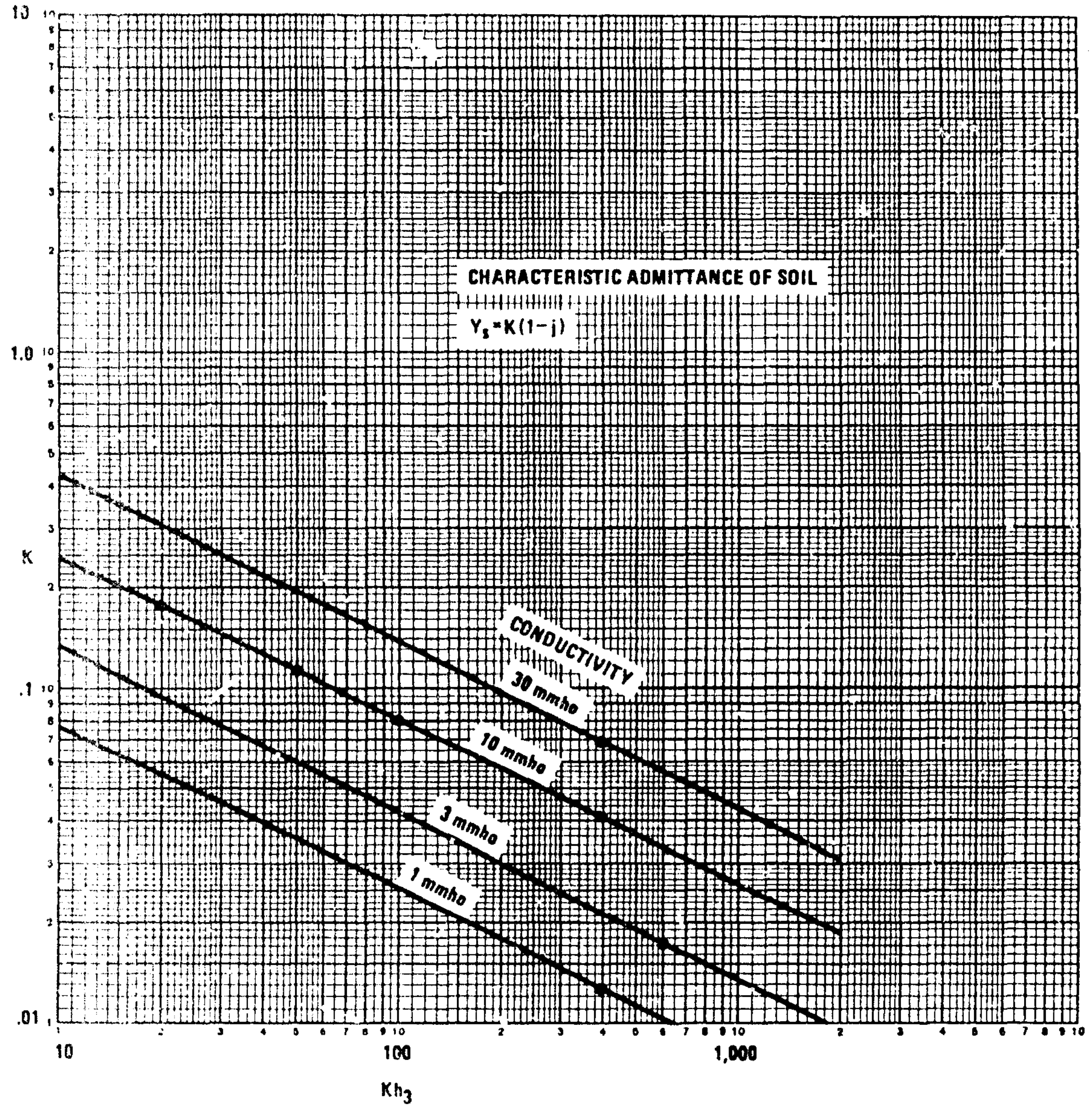


REV A J13-9

Figure 16. Characteristic Admittance of Soil

$$Y_G = -j \frac{1}{f\mu d \, \log_e \frac{d}{2\pi a}} \tag{25}$$

f frequency

μ permeability

d wire spacing

a wire radius

This can be used for a radial ground system since losses are summed from meter square segments for which the wires may be considered parallel. Values for this admittance are shown in Figure 17. Normally the total current flows in the sum of these two admittances and the loss is computed for that portion which flows in the real part of Y_S.

However, to find where the critical areas are for designing the ground system, we will calculate the loss with no physical ground wires but considering a lossless theoretical connection to the earth to skin depth.

Loss per unit area = I^2/Real part of Y_S

The radial H field current distribution from the base of the element (Reference 2) for a constant current of one ampere in the antenna is

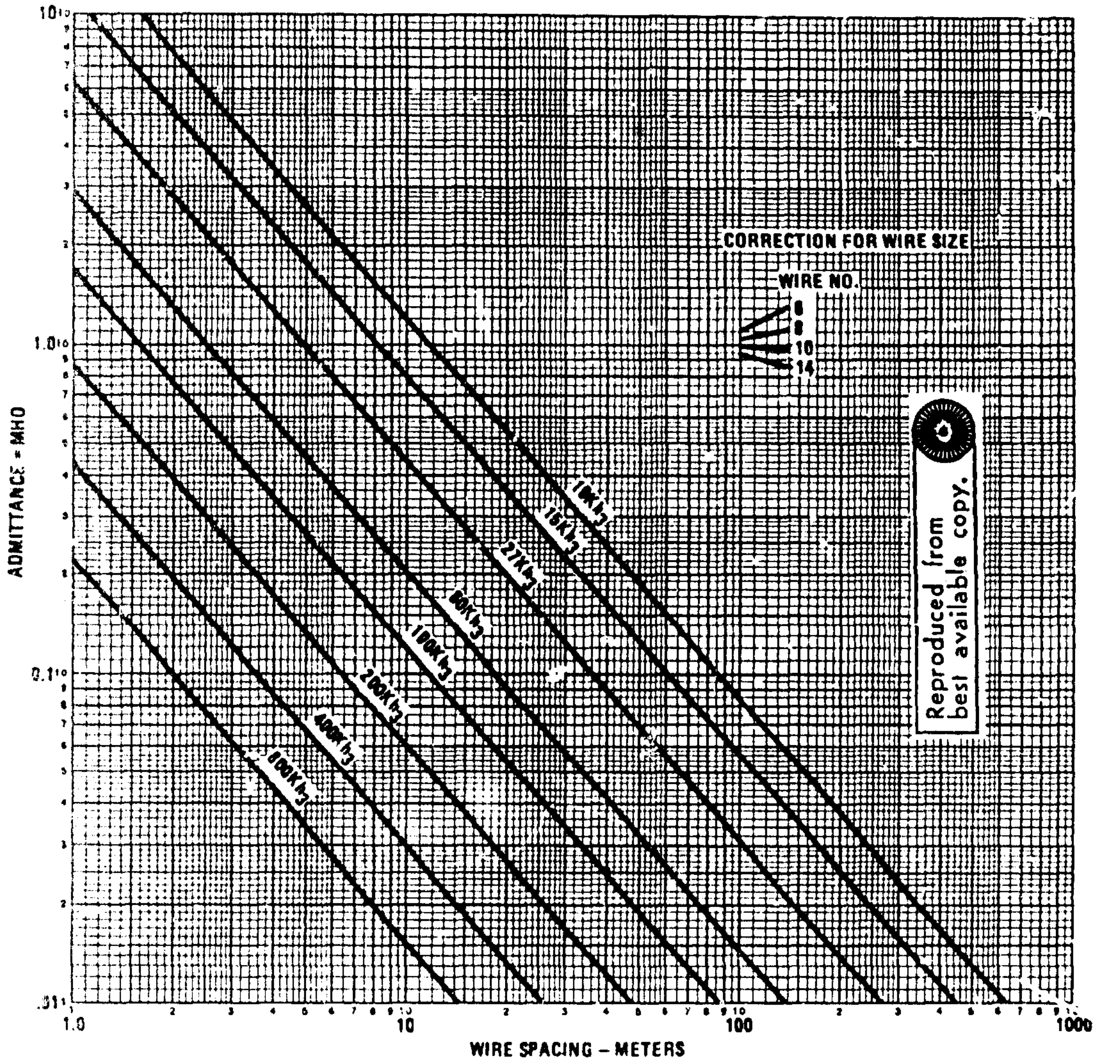
$$I_\eta = \frac{h}{2\pi D \sqrt{h^2+D^2}} \tag{26}$$

h antenna height

D distance

I amperes per meter

This is termed the near H field in Figure 18. The expression is not valid for the far field, which at a distance of $1/2\pi$ meters, must satisfy the expression



REV A J13-8

Figure 17. Admittance of Wire Screen No. 8 Wire

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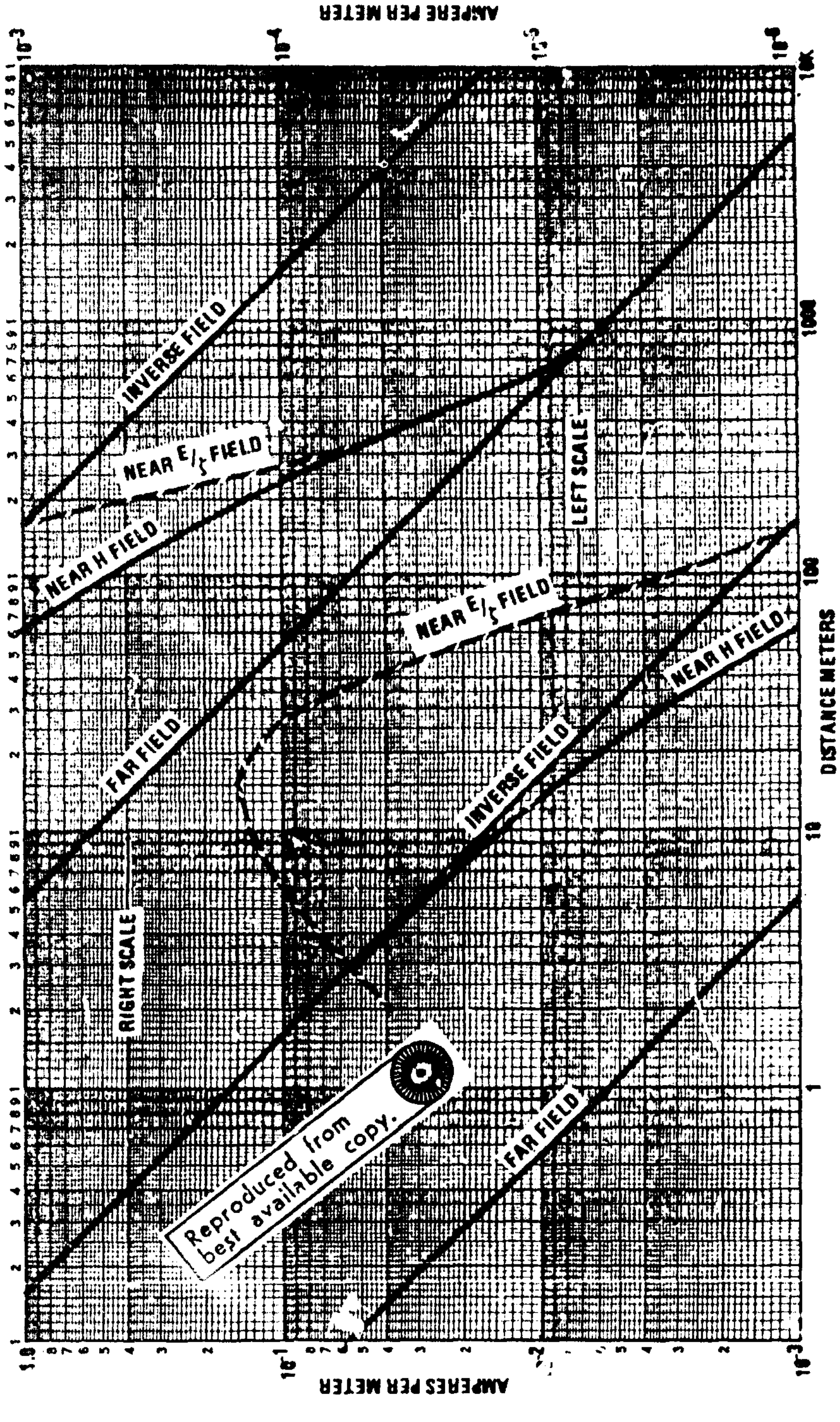

Figure 18. E & H Field Near 100-Foot Constant Current Antenna

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$$I_f = \sqrt{\frac{R_a}{R_{\lambda/4}}} \tag{27}$$

R_a radiation resistance of subject antenna

$R_{\lambda/4}$ radiation resistance of a quarterwave antenna

A quarterwave antenna has a close and far lossless current distribution which is inversely proportional to distance and will equal one ampere per meter at a distance of $1/2\ \pi$ meters.

$$I_f = \frac{.0426}{36} = .0344 \text{ amperes per meter.} \tag{28}$$

The inverse field and this far field are also shown in Figure 18. The ground system need not extend beyond the distance where the near field intersects the far field, since the far field current results from radiation alone.

We must examine the losses to a distance of 600 meters for this antenna. From Figure 16, the characteristic admittance of soil at 27 kHz is

$$\sigma = 1,\ Y_S = .046 - j.046 \tag{29}$$

$$\sigma = 3,\ Y_S = .08 - j.08 \tag{30}$$

$$\sigma = 10,\ Y_S = .15 - j.15 \tag{31}$$

The ground area is segmented into annular rings, the first being 10 meters in radius and the balance in 20 meter increments. The power loss per segment then is

$$P_S = \frac{I_S^2 \times A}{Y_S \text{ (real)}} \tag{32}$$

I_S average current per segment (Figure 3)

A area per segment

The values of loss in the ground per ampere in the antenna is cumulated from the base outward as shown in Figure 19.

The E field loss is also shown in Figure 19 and is calculated by finding the depth of a solid conducting plane that is equivalent to the ground system and then finding the I^2R loss due to current flowing in the capacitor from the surface of the ground to this solid conducting plane. The resistance of the soil is

$$R_S = \frac{h\,\sigma}{\sigma^2 + (\omega\varepsilon_s)^2} \qquad (33)$$

h equivalent screen depth

σ conductivity

ω $2\pi f$

ε_S earth permittivity

for all practical soils $\sigma >> \omega\varepsilon_s$, therefore

$$R_s = \frac{h}{\sigma} \qquad (34)$$

the power loss is

$$P_{se} = \frac{I_s^2 h}{\sigma} \qquad (35)$$

since the current in the soil equals the displacement current directly above the surface

$$I_S = I_d = \omega\varepsilon E \qquad (36)$$

ω $2\pi f$

ε air permittivity

E electric field strength

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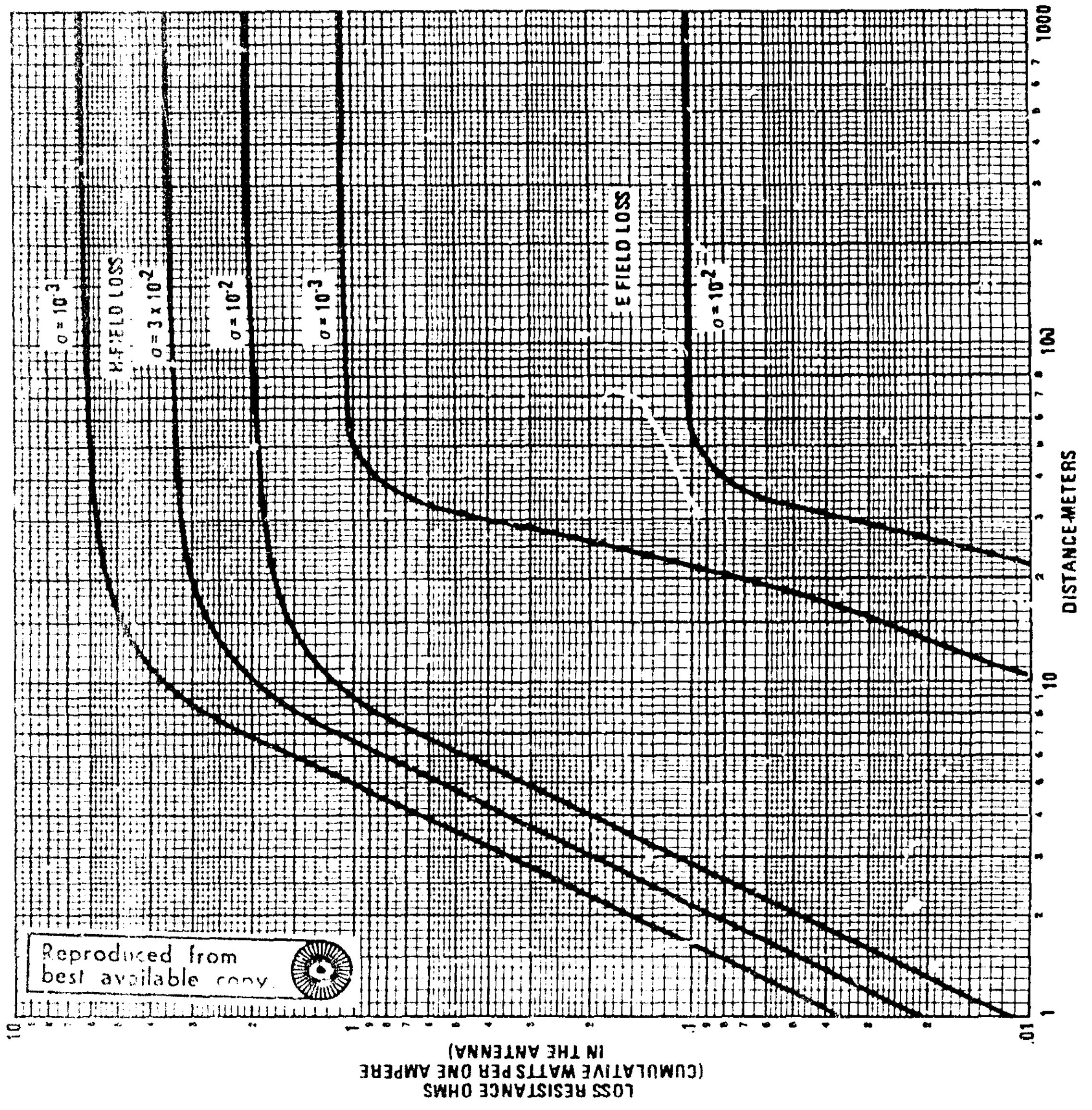

Figure 19. E & H Field Losses in Ground System

REV A J13-6

The power loss then is

$$P_{se} = \frac{E^2 (\omega\varepsilon)^2 h}{\sigma} \tag{37}$$

For clarity, let $\ell = \frac{(\omega\varepsilon)^2}{\sigma}$, which is calculated and plotted in Figure 20 as the specific E field loss. Then

$$P_{se} = E^2 h \ell \tag{38}$$

The E field ratio to the H field as given by Tove Larsen (Reference 2) is shown in Figure 21 is constant current top loaded antennas. This curve has also been placed on Figure 18 to show reference distance. To examine the losses without a ground system, h is taken at skin depth in the earth or 98 meters for the lowest conductivity. The E field loss is cumulatively shown in Figure 19.

Examination of Figure 19 shows that there is no more than a two ohm contribution to the H field losses beyond 10 meters from the antenna for the worst soil. The total E field loss is one ohm and lies in the area between one-half and one-tower height, 15 - 30 meters.

It appears that a minimum ground system under the top load wires and within 10 meters of the element bases will result in no more than 3 ohms ground loss per element for the system. We had estimated a ground loss of 3.33 ohms in our proposal to achieve the performance requirements.

To evaluate the calculations, a minimum ground system for the model was installed as shown in Figure 22. Analysis was made to convert the findings from the model frequency to the operating frequency range for the full scale antenna.

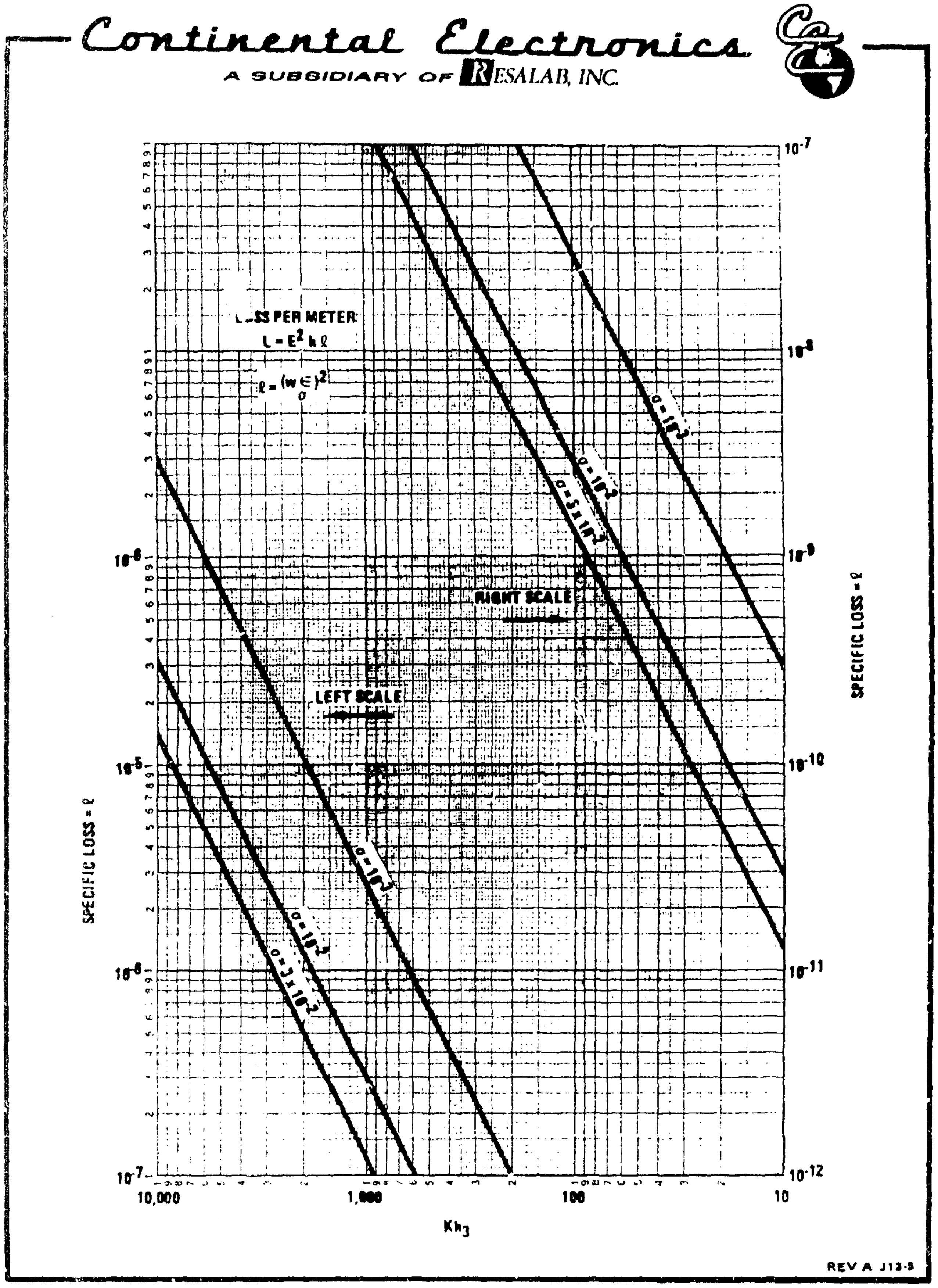

Figure 20. Specific E Field Loss

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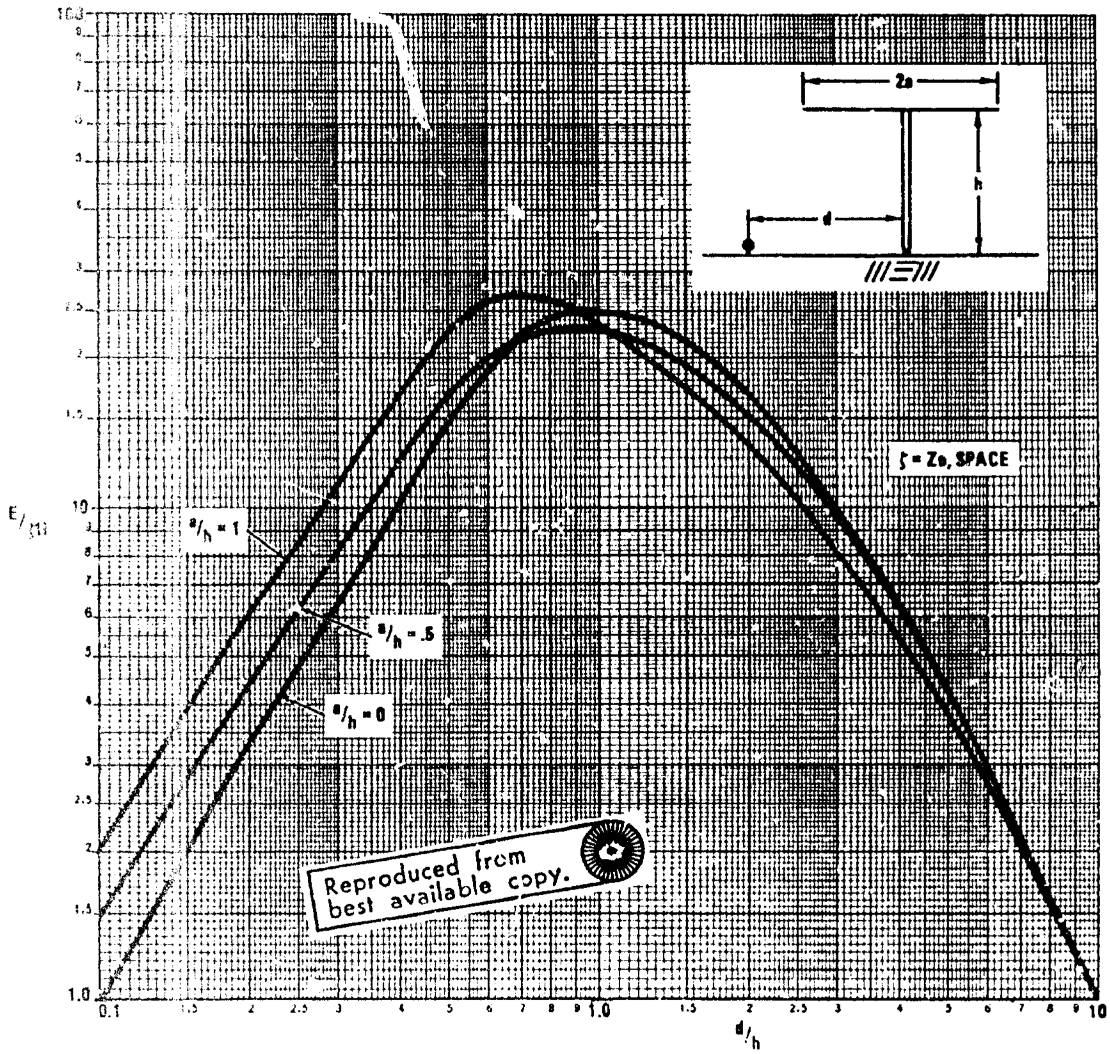

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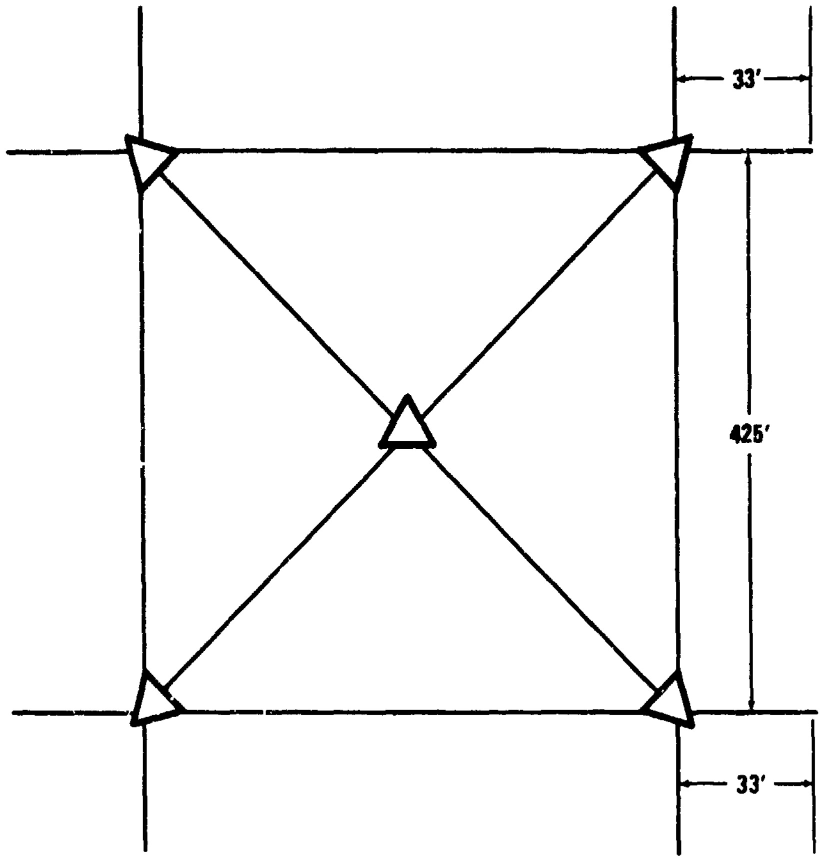
Figure 21. Ratio of E to H Fields, Constant Current



NOTE

DIMENSIONS SHOWN TYPICAL
ALL FOUR SIDES

REV B J13-12

Figure 22. Model Ground System for Test

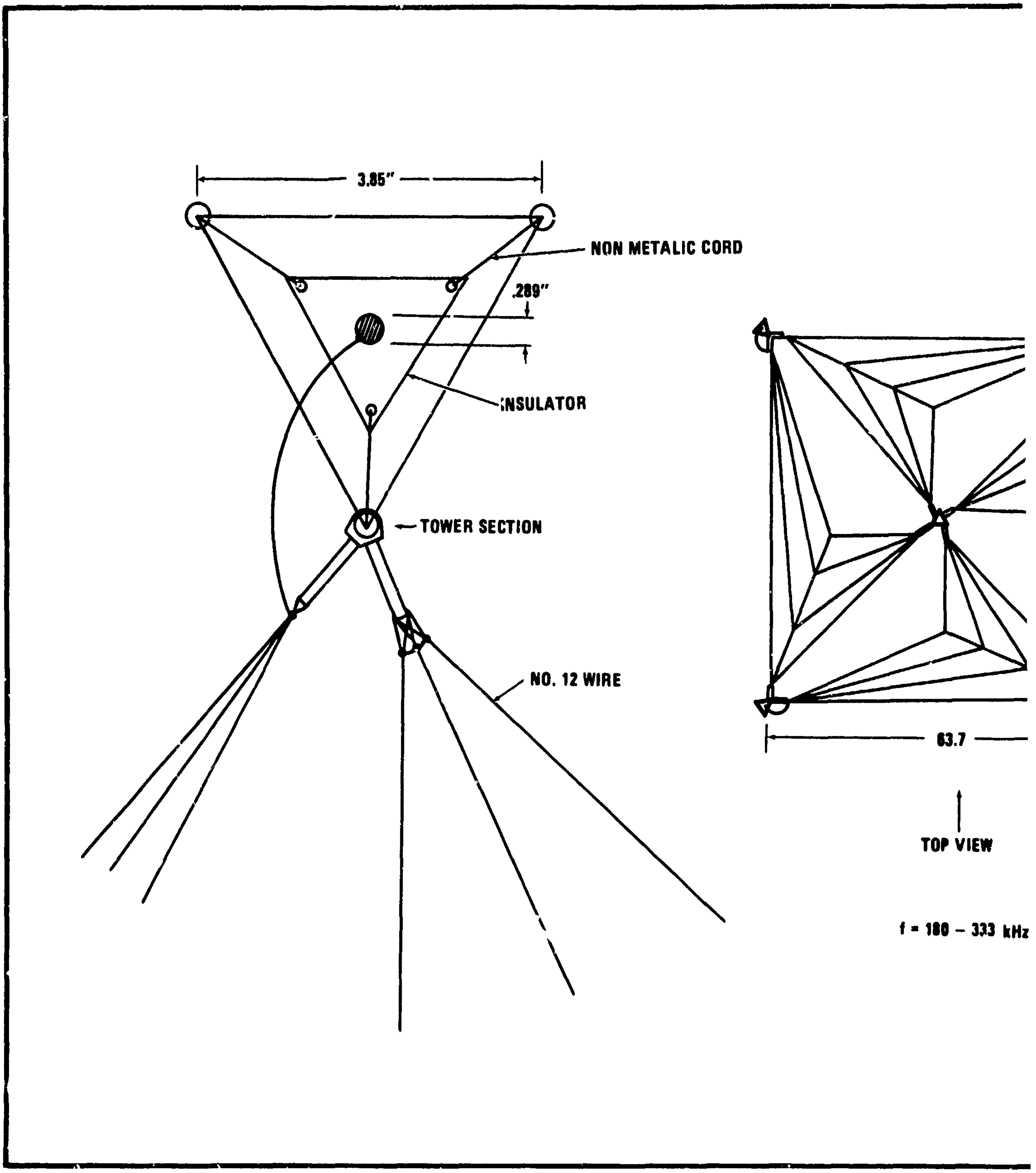
SECTION VI

MODEL DESIGN

The evaluation model for this program was contractually required to be at a scale not exceeding 10:1. A smaller scale ratio will result in more accurate work and we proposed to use a scale ratio of 6.66. This ratio was chosen due to the limitation of our available field intensity set which has a lower frequency limit of 150 kHz.

The model constructed was 63.7 feet on a side and 15 feet high as shown in Figure 23. The scale model has the equivalent of 1/2 diameter conductors in the top hat and a solid conductor in the towers which simulates a three-wire cage to forestall corona. This is equivalent to a two-inch single conductor in the final antenna. It may be feasible to install a two-inch aluminum tube to eliminate the three-wire cage. This will need further study.

A


3.85"
NON METALIC CORD
.289"
INSULATOR
TOWER SECTION
NO. 12 WIRE
63.7
TOP VIEW
f = 180 – 333 kHz

B

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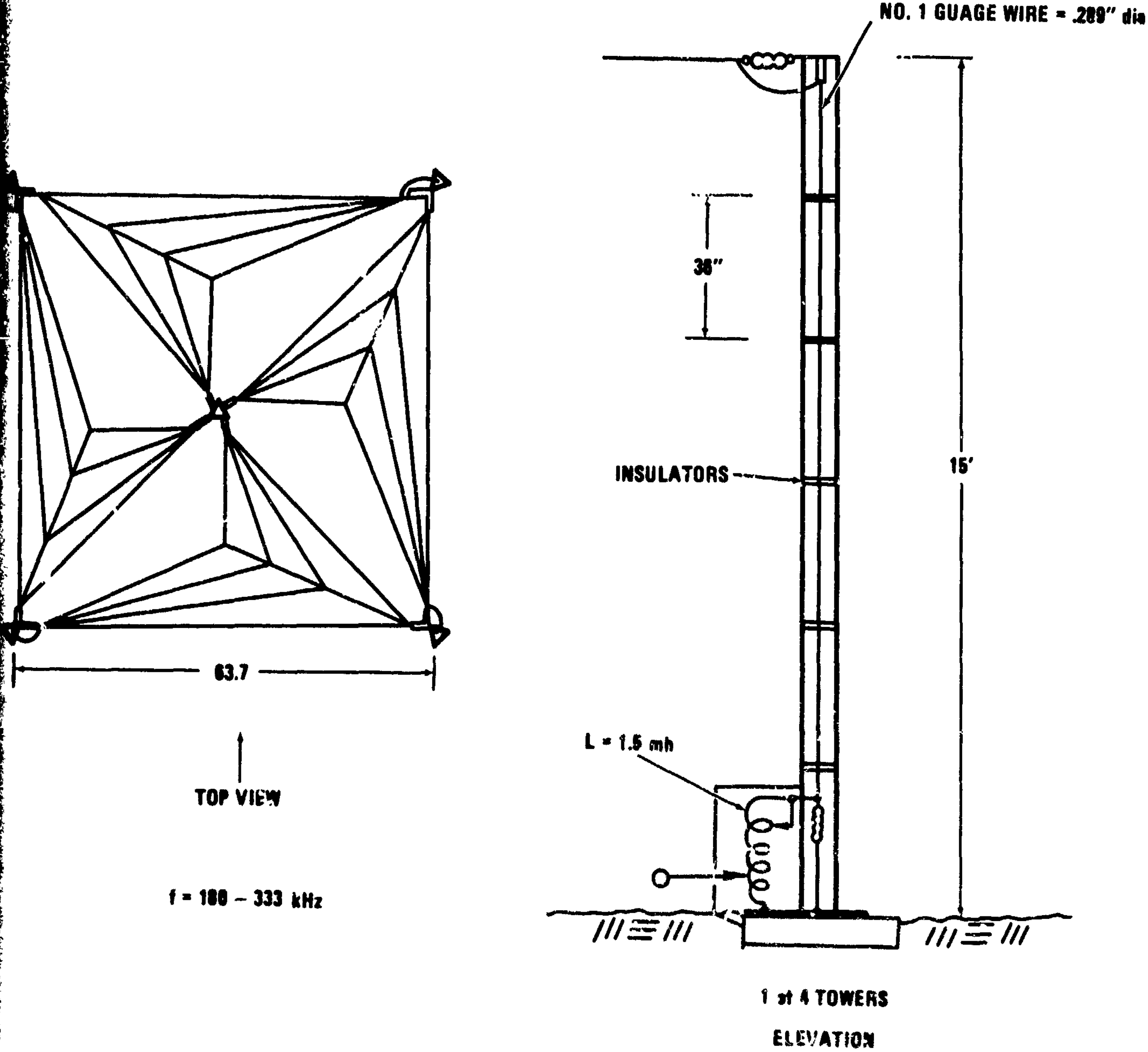

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Figure 23. RADC Model Paran

SECTION VII

MODEL PERFORMANCE

The scale model was installed and driven with 100 watts of power. Field intensity measurements indicated an efficiency of 0.198% additional ground radials were added as shown in Figure 24, which improved the efficiency to 0.226%. Field intensity measurements are shown in Figure 25. An analysis of the system loss shows the following distribution.

Power radiated		0.226 watts
Coil Losses		72.000 watts
Ground System Losses		27.774 watts
	Power Input	100.000 watts

The effective height for the model measured 14.32 feet. The measured bandwidth efficiency product was 2.08 Hz. At the design goal efficiency of 0.5%, the antenna bandwidth is

$$B\omega = \frac{2.08}{\eta} \quad , \quad \eta = .005 \tag{39}$$

$$B\omega = 416 \text{ Hz} \tag{40}$$

with matched transmitter loading, the system bandwidth will be 832 Hz.

The ground losses will reduce approximately as the square root of the model scale

$$L_G = 27.774\sqrt{\frac{1}{6.666}} \tag{41}$$

$$L_G = 10.5 \text{ watts or } 10.5\% \tag{42}$$

This is close to the performance predicted for 27 kHz. However, the coil losses are much higher than was predicted and could not be accounted for by usual coil design methods. It was, therefore, decided to make a study of coil losses and develop reliable prediction methods so that the full scale antenna design and performance can be assured.

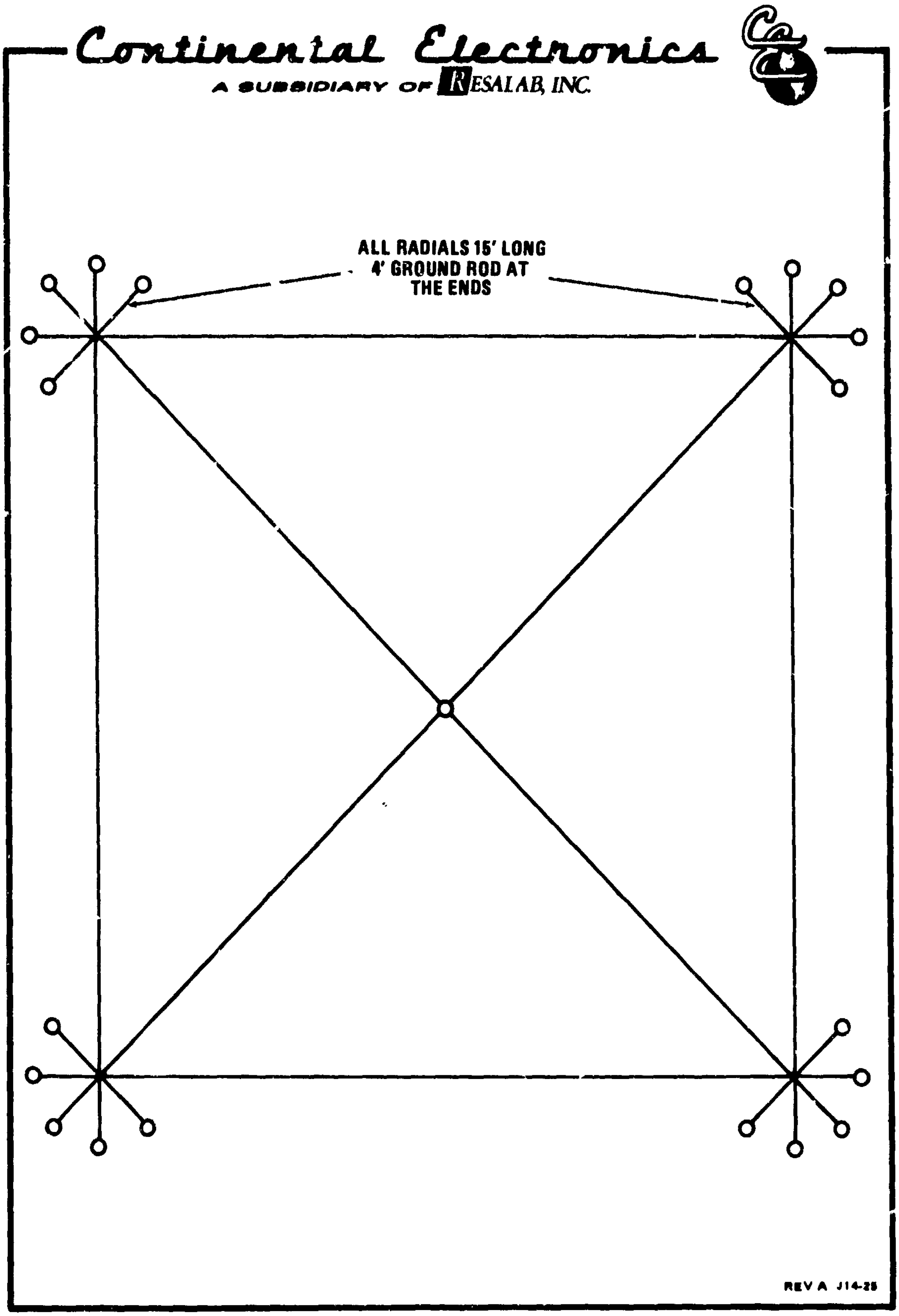

Figure 24. Modified Ground System

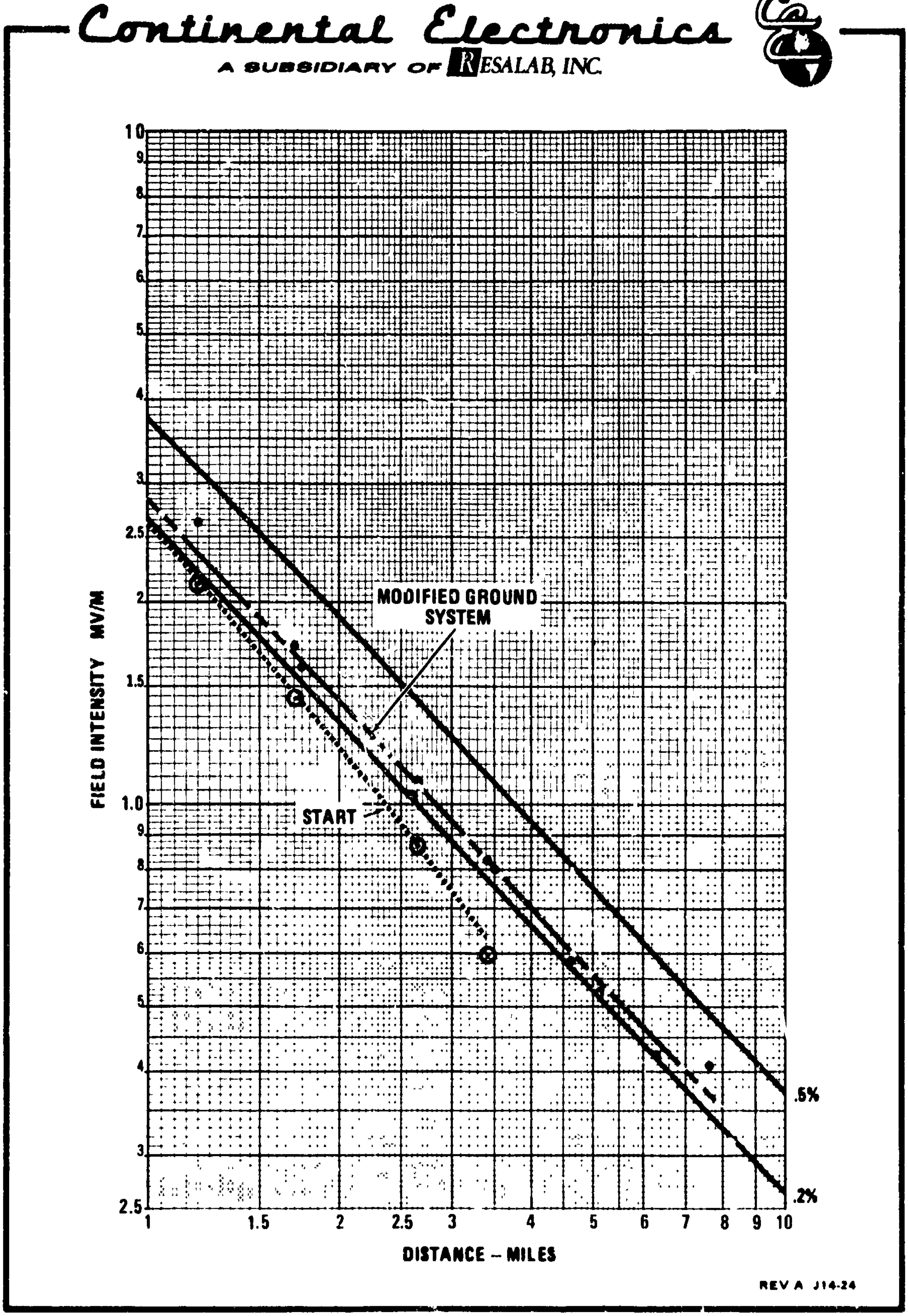

Figure 25. Field Intensity Measurements

SECTION VIII

INDUCTOR LOSSES

Numerous works on inductors and their losses are to be found in literature. The most extensive work on inductor loss is that of Butterworth (Ref. 5) who considered a coil as short cylindrical parallel sections of conductor, and determined losses as the result of the magnetic fields produced. For single layer solenoids, the ac resistance, as related to the dc resistance, is given by

$$\frac{ac}{dc} = H + \mu\left(\frac{d_o}{c}\right)^2 G \tag{43}$$

H is the skin effect of each conductor and the next term is the mutual coupling or proximity effect between the turns. The tables of Butterworth are published by Terman (Ref. 6) wherein the values of H are related to his function

$$\chi = \pi d \sqrt{2f/\rho} \tag{44}$$

for copper

$$\chi = 0.1078d \sqrt{f} \tag{45}$$

d = wire diameter, Cm

f = frequency, Hz

Values of χ are shown in Figure 26 for the frequency range of interest. The values of H in this range of conductors and frequency are shown in Figure 27 as taken from the referenced tables. G from those tables is shown in Figure 28. The parameter μ from the tables is plotted in Figure 29. The quantity $d_{o/c}$ is simply the wire diameter divided by the spacing between turns and has been plotted for convenience in Figure 30.

The first fabricated test Coil A is shown in Figure 31. This coil was designed to have the inductance required for the scale model PARAN antenna now undergoing study. Figure 32 shows the measured impedance of Coil A and Figure 33 shows the measured Q.

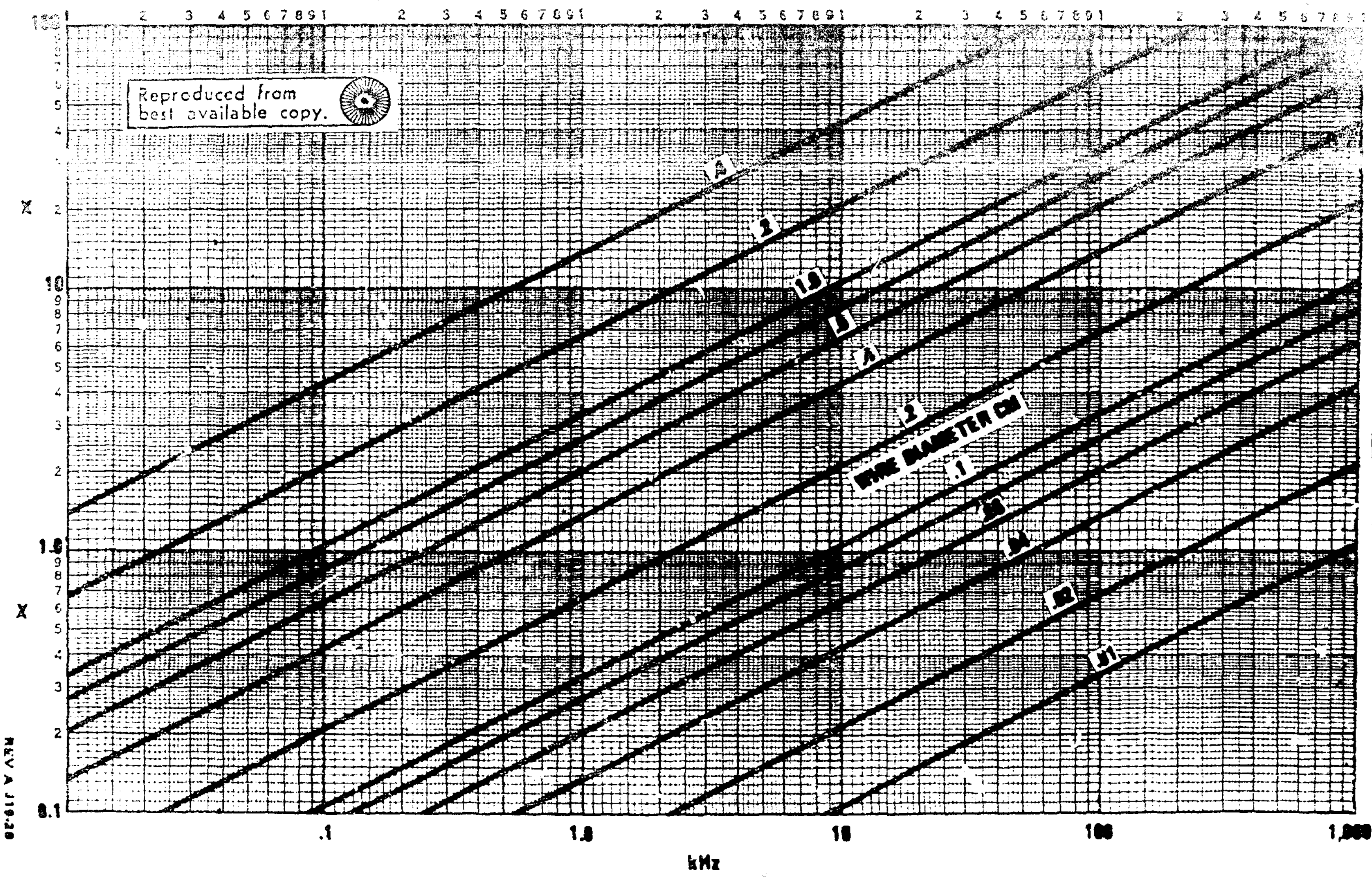

Figure 28. X Function - Coil Losses

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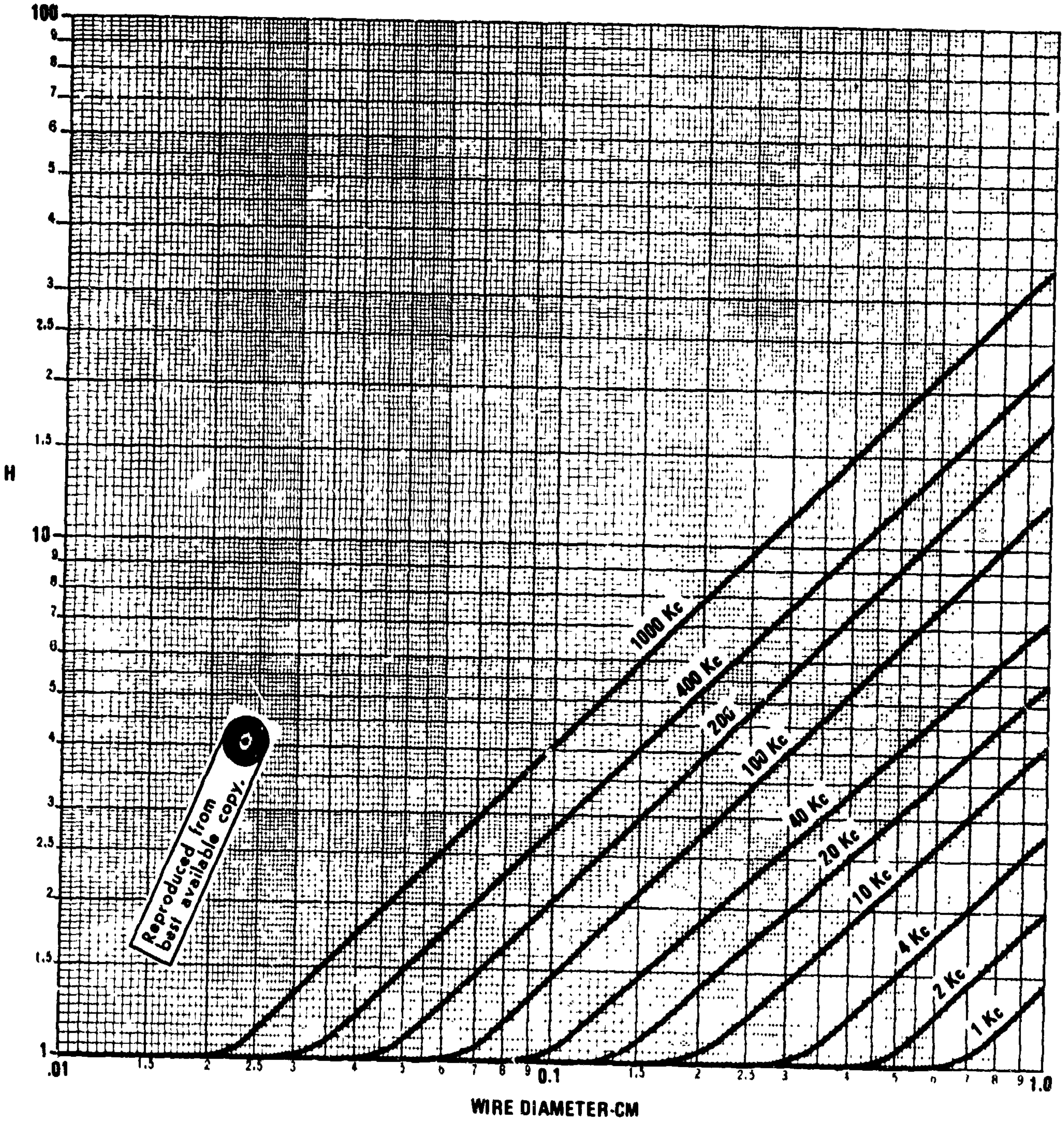

Figure 27. H-Function Skin Effect

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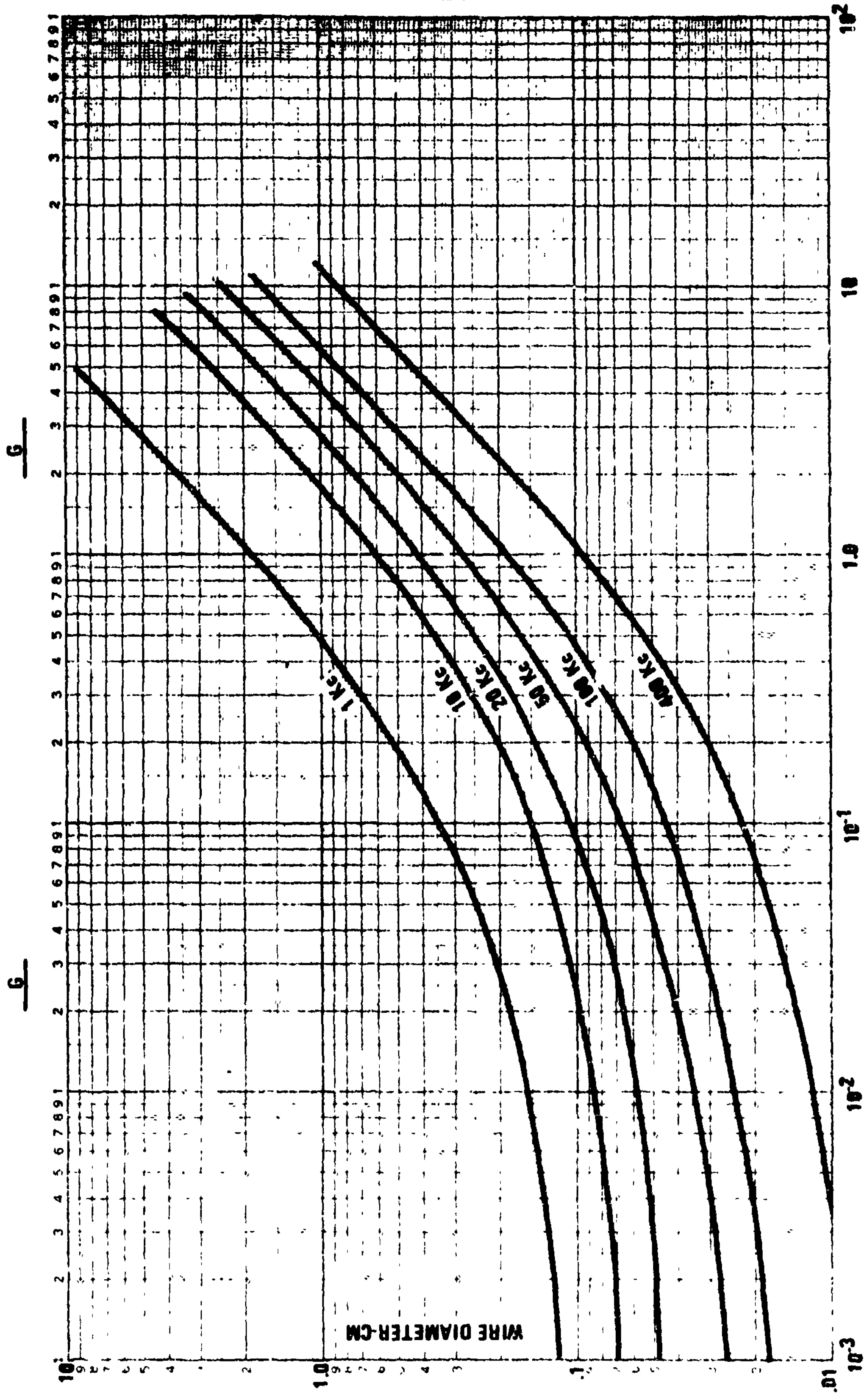


Figure 28. G Function Proximity Effect

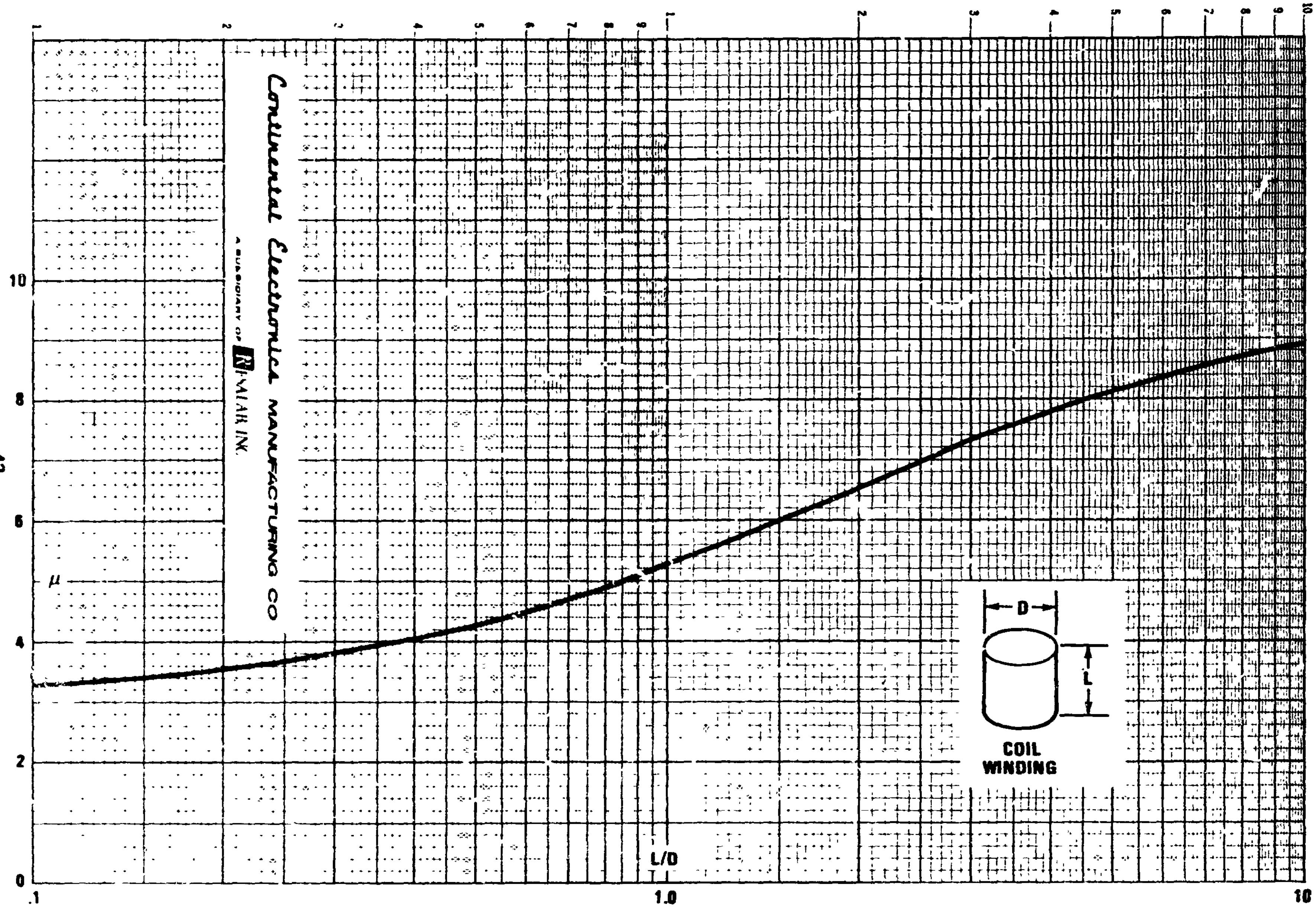


Figure 29. μ Function Proximity Effect

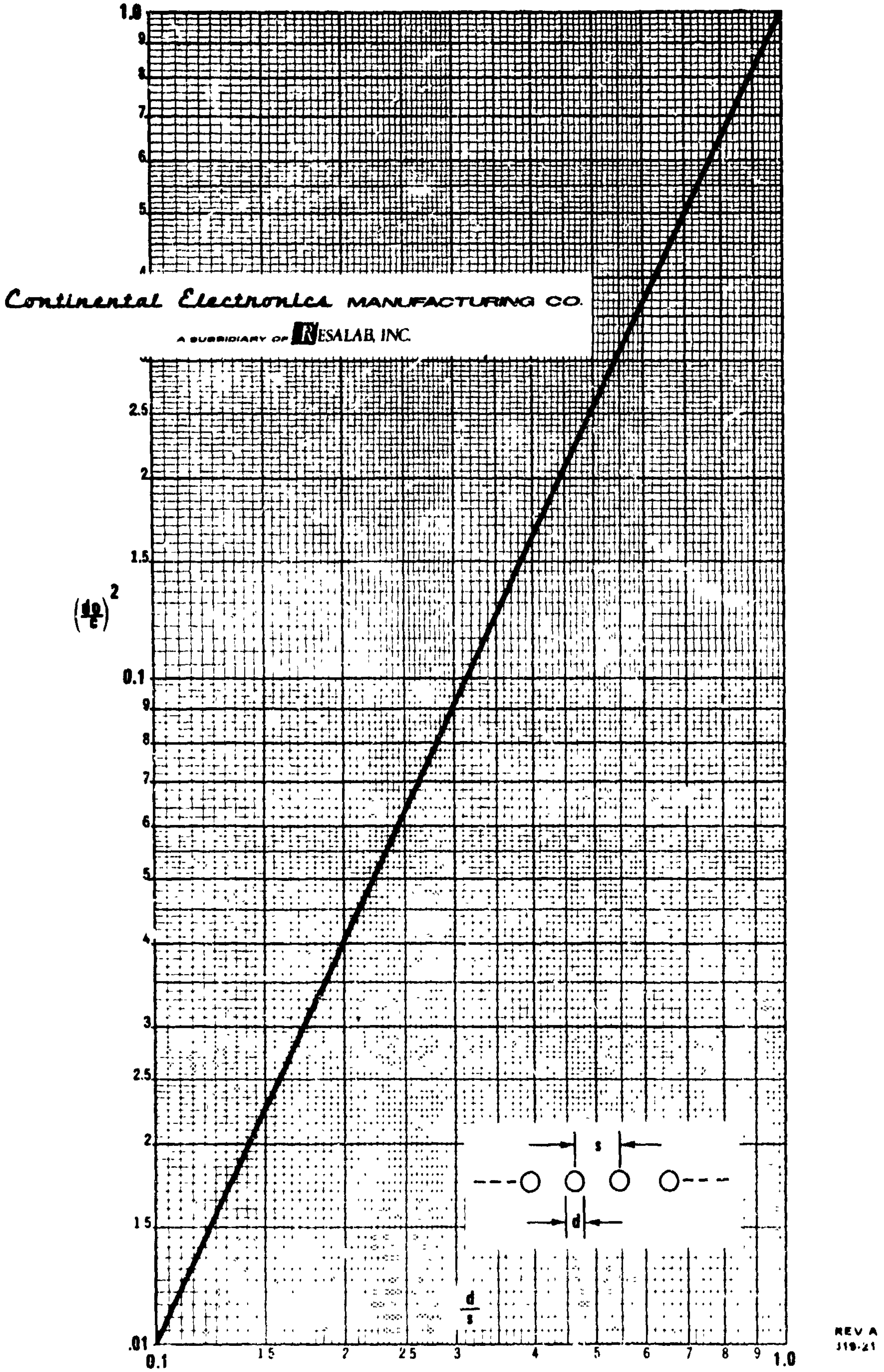
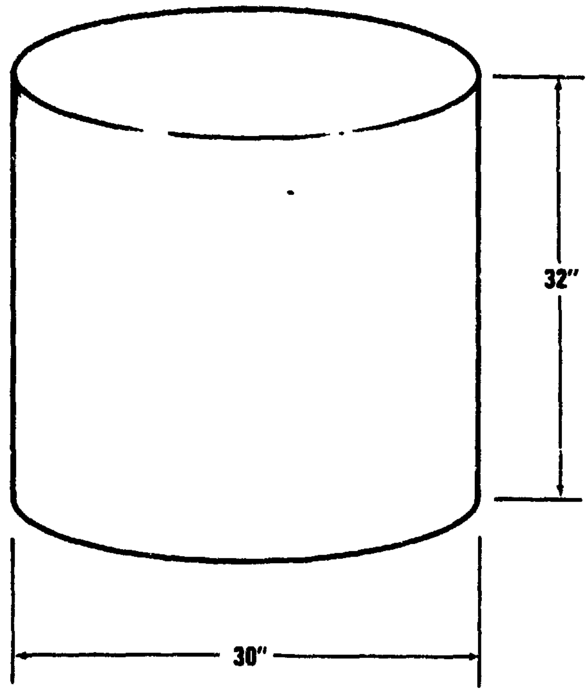


Figure 30. Spacing Function Proximity Effect



64	TURNS
1/4	INCH OD COPPER TUBE
.035	INCH WALL THICKNESS
.025	SQUARE INCHES COPPER CROSS SECTION AREA
500	FEET LENGTH OF CONDUCTOR
DC	RESISTANCE 0.32 OHMS PER 1,000 FEET
1/2	INCH SPACING BETWEEN TURNS
480 kHz	SELF RESONANT FREQUENCY

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Figure 31. Test Coil A

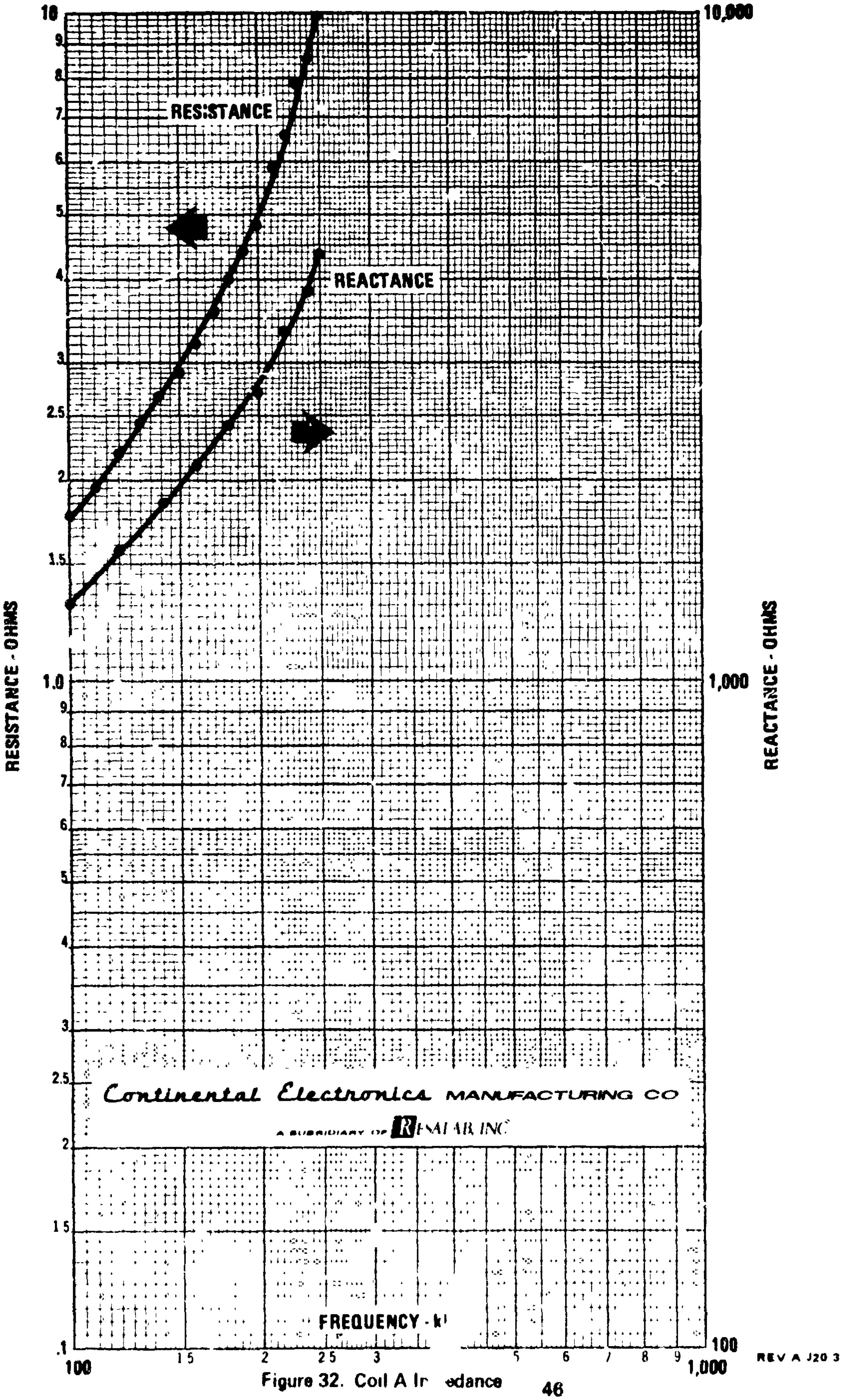

Figure 32. Coil A Ir edance

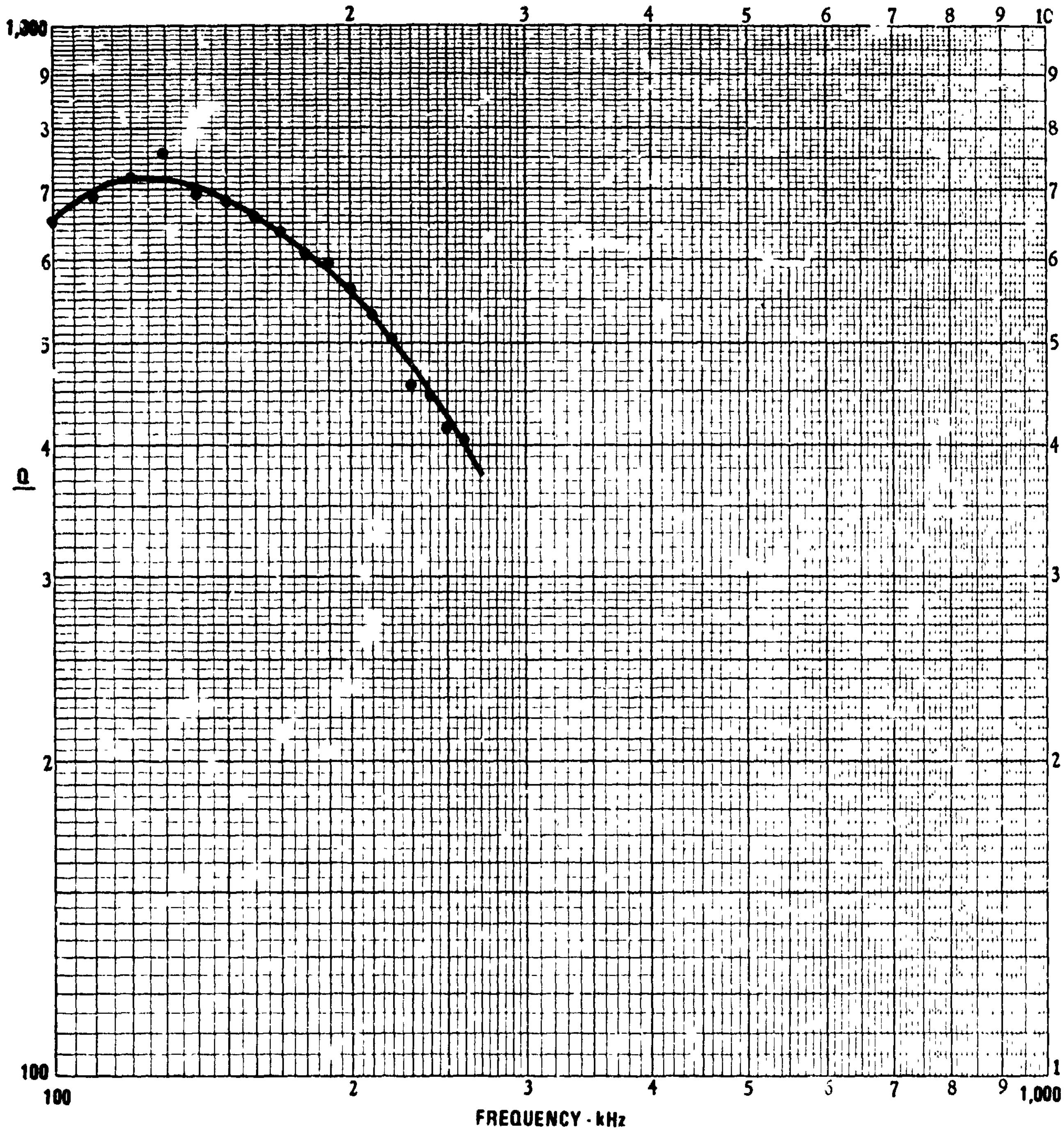

Figure 33. Coil A Measured Q

Figure 34 shows the measured loss performance of Coil A compared with the calculated values. The measured loss resistances were normalized to ohms-per-thousand-feet of conductor for easy comparison of inductors and published wire data. The copper tubing cross sectional area is equal to a round wire of 0.18 centimeters in diameter.

It can be seen that below 100 kHz, the measured values equal the predicted values of loss resistance. Above this frequency, the measured values diverge upward quite rapidly. Further measurements show that this coil is going into parallel resonance with its distributed capacity and that this resonant frequency is 480 kHz. The peak in the Q of this coil from Figure 28 is at a frequency of 120 kHz and the roll-off of the Q above this frequency is due to approaching resonance.

Terman (Ref. 7) has shown that the increase in resistance as resonance is approached is

$$\frac{R\ \text{total}}{R\ \text{actual}} = \frac{1}{\left(1 - \gamma^2\right)^2} \tag{46}$$

Where γ is the ratio of the working frequency to resonance frequency. This term has been calculated and is shown in Figure 35. By applying this ratio from Figure 35 to the known ac series resistance of the coil above 100 kHz from Figure 34, an analysis of the measured coil performance as compared with the calculated performance is shown in Figure 36.

The expression for inductors wound with multi-strand insulated Litz wire (Ref. 8) is

$$\frac{\text{ac Resistance}}{\text{dc Resistance}} = H + \left[K + \mu\left(\frac{d_o}{c}\right)^2\right]\left(\frac{ds}{d_o}\right)^2 \eta^2 \quad G \tag{47}$$

η = number of strands
ds = diameter of individual strands

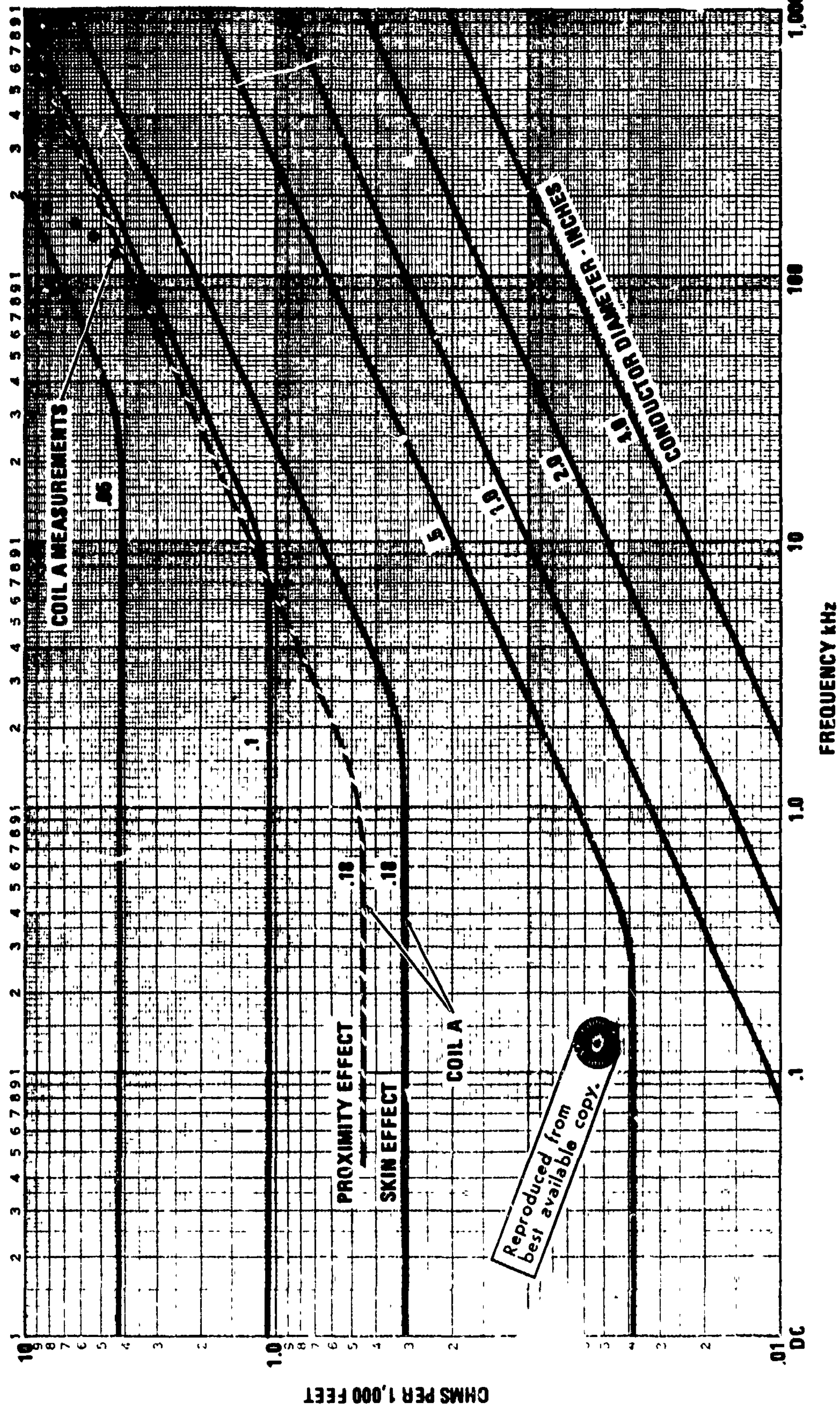

Figure 34. Coil A Loss Performance

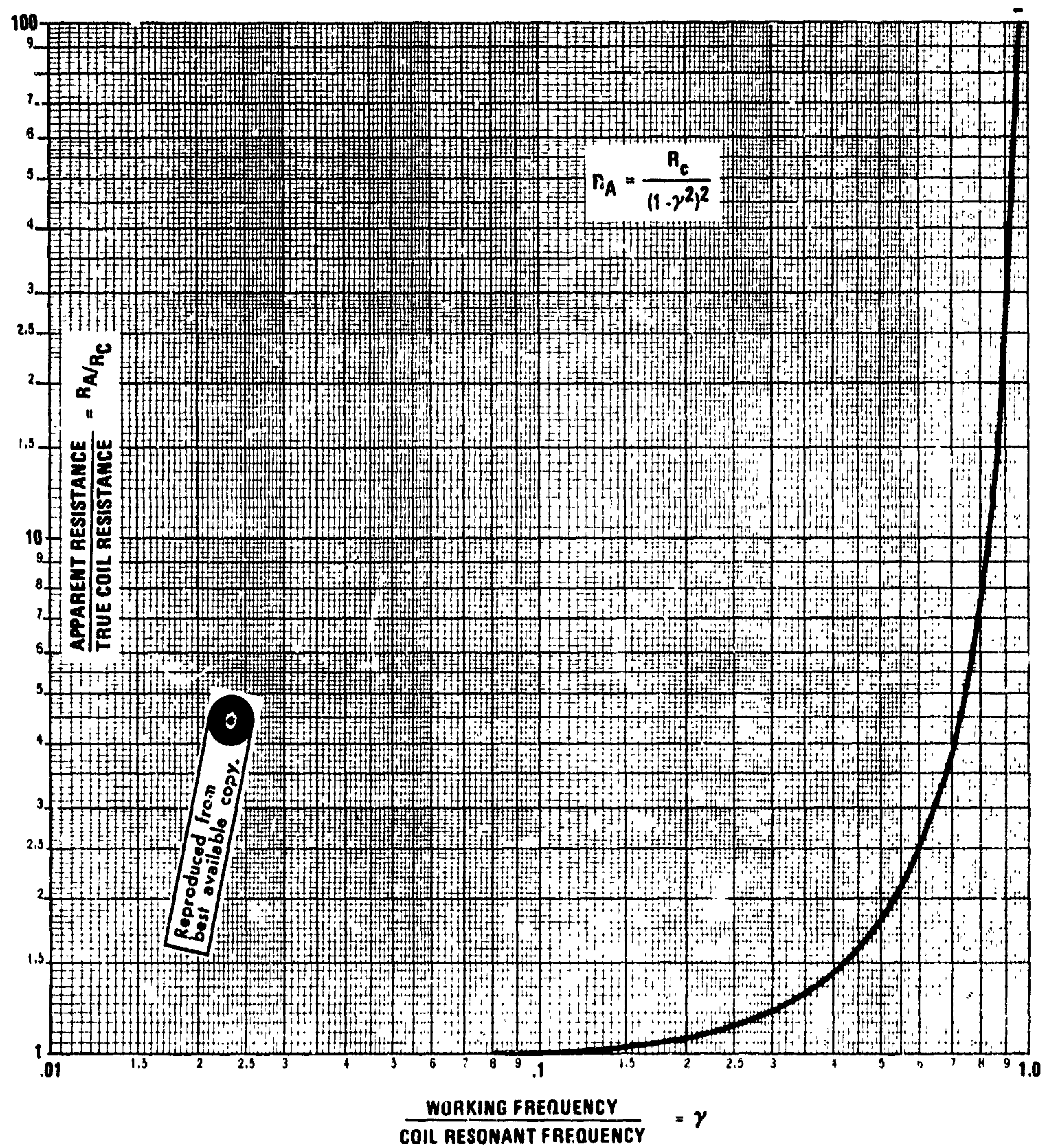

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Figure 35. Effect of Parallel Resonance in Coils

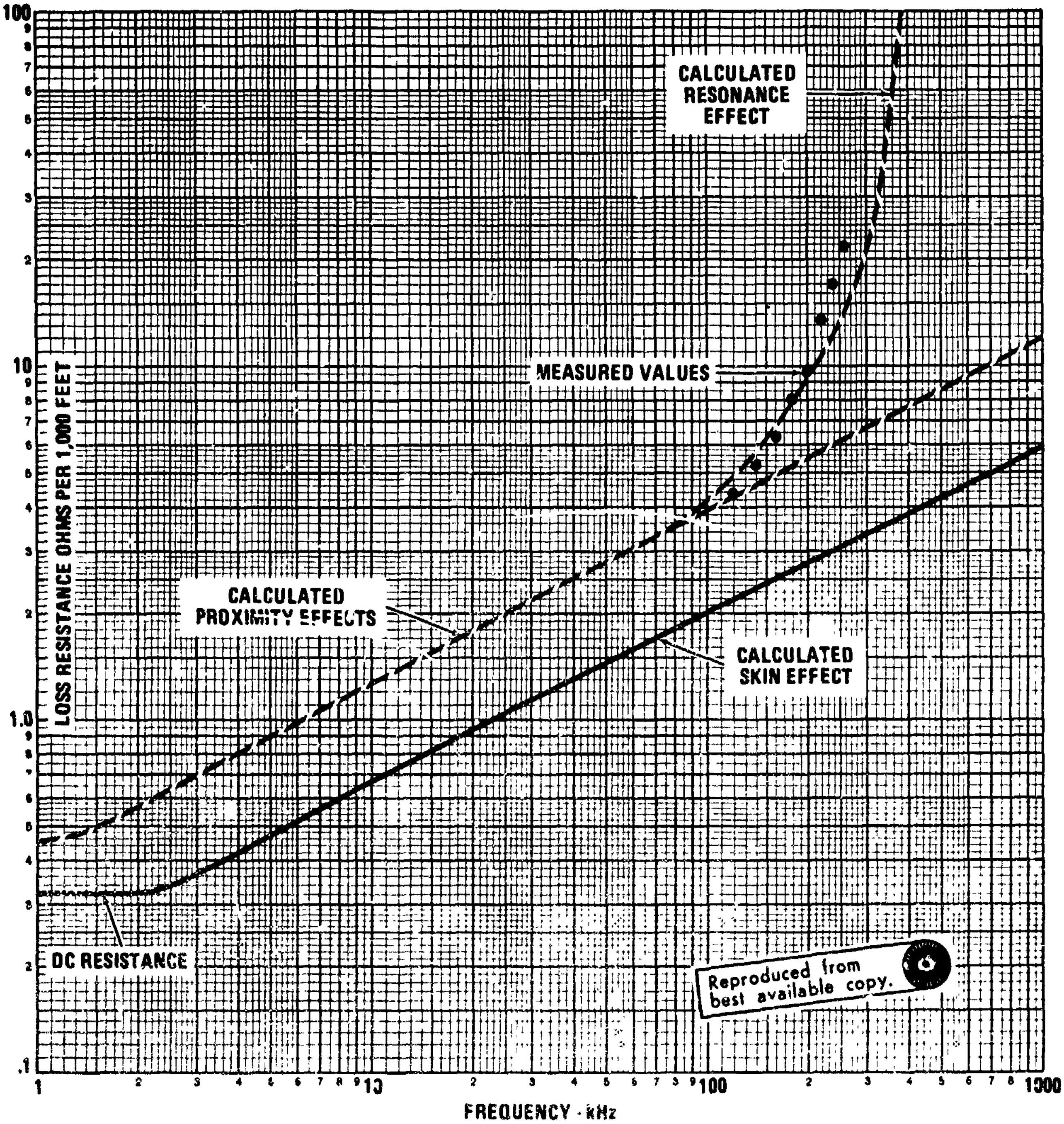

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Figure 36. Coil A Analysis

d_o = diameter of the cable

G is shown in Fig. 28 (use strand diameter)

H is shown in Fig. 27 (use strand diameter)

K = 1.55 for η = 3, 1.84 for η = 9, 1.92 for η = 27, 2 for $\eta = \infty$.

It can be seen, that if the diameter is small, (less than skin depth, then H from Figure 27 is unity, and G from Figure 28 is less than 10^{-4} and $\left(d_s/d_o\right)^2$ is of the order 10^{-3} and

$$\frac{ac}{dc} = 1.0 \text{ (as a limit)} \tag{48}$$

which says that, if the strand size is small enough at low frequencies, both the skin effect and proximity effect disappear.

Numerous other coils having varied configurations were fabricated and measured. It was found that below the frequency where parallel resonance effected the Q, the loss resistance could be predicted with good accuracy. It was further found that losses due to parallel resonance could not be predicted accurately and since the losses rise rapidly above a critical series reactance (about 1500 ohms), it is undesirable to utilize coils with this characteristic in the RADC antennas.

The best aspect ratio for minimizing coil losses is a coil length approximately equal to its diameter, however, this is a slowly varying function and is not critical. A universal set of design curves is shown in Figure 37 giving the loss per thousand feet of conductor with this aspect ratio and a conductor spacing equal to one conductor diameter. The values shown for Litz wire are calculated from theory as our available instrumentation was not accurate for Q's over 1000. We found that the resonance effect noted also increased the losses in Litz coils having reactances above 1500 ohms.

Losses to be expected by shielding enclosures of inductors is given by Howe (reference 9).

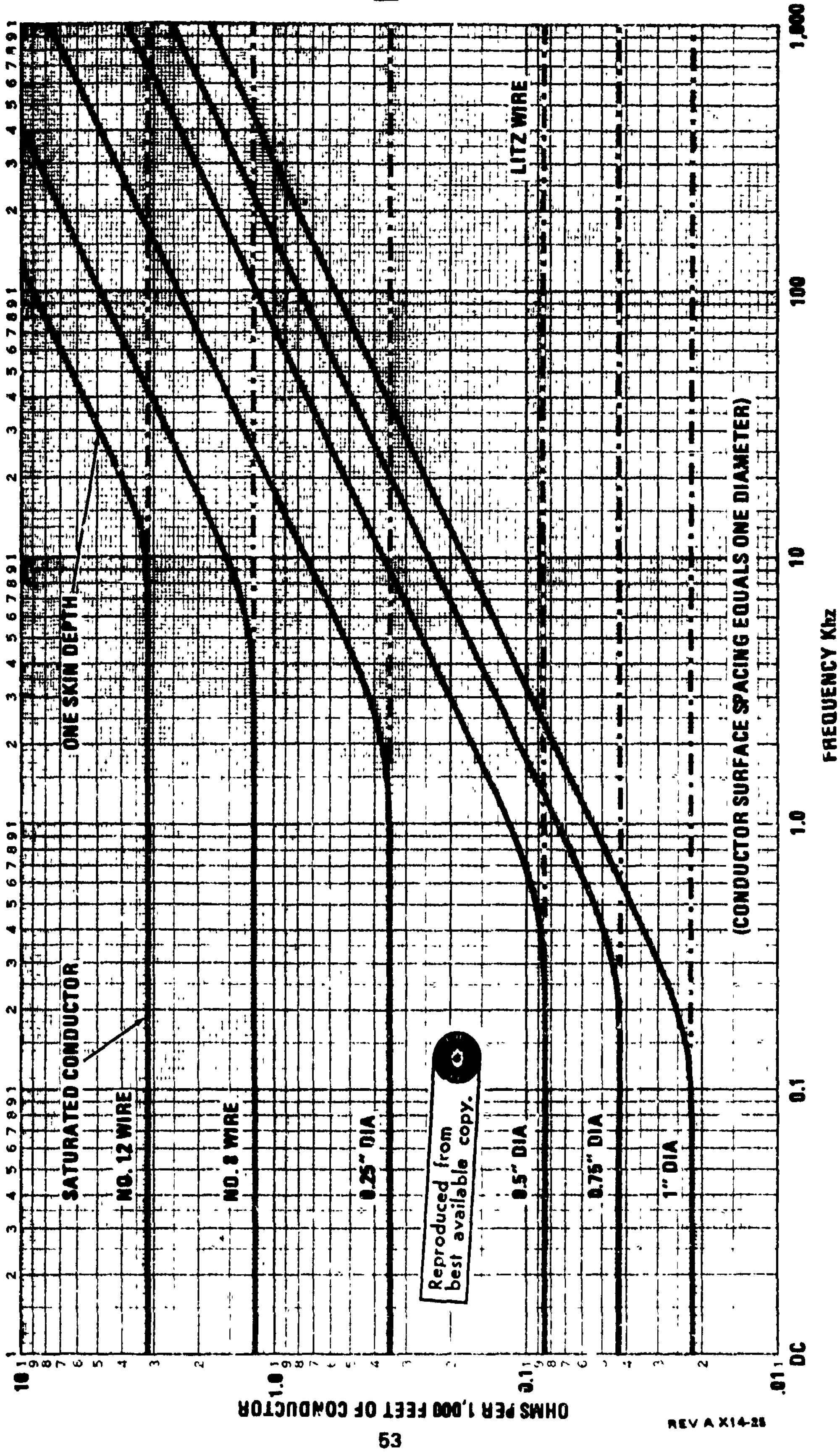

Figure 37. Coil Loss Design Curves

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$$R_s = \frac{9.37 \times 10^{-4} \; N^2 \, \nu_c^{\,4} \, \sqrt{f}}{\nu^{\,4}} \tag{49}$$

N = number of turns

ν_c = radius of coil

ν = radius of spherical shield

f = frequency in Hertz

ρ = resistivity of shield = 1.727×10^{-6} for copper

R_s = coil series resistance

For rectangular shields, the mean dimensions approximating an equivalent sphere may be used. The solution for this equation is shown in Figure 38 at 100 kHz, and can be applied to other frequencies as shown thereon.

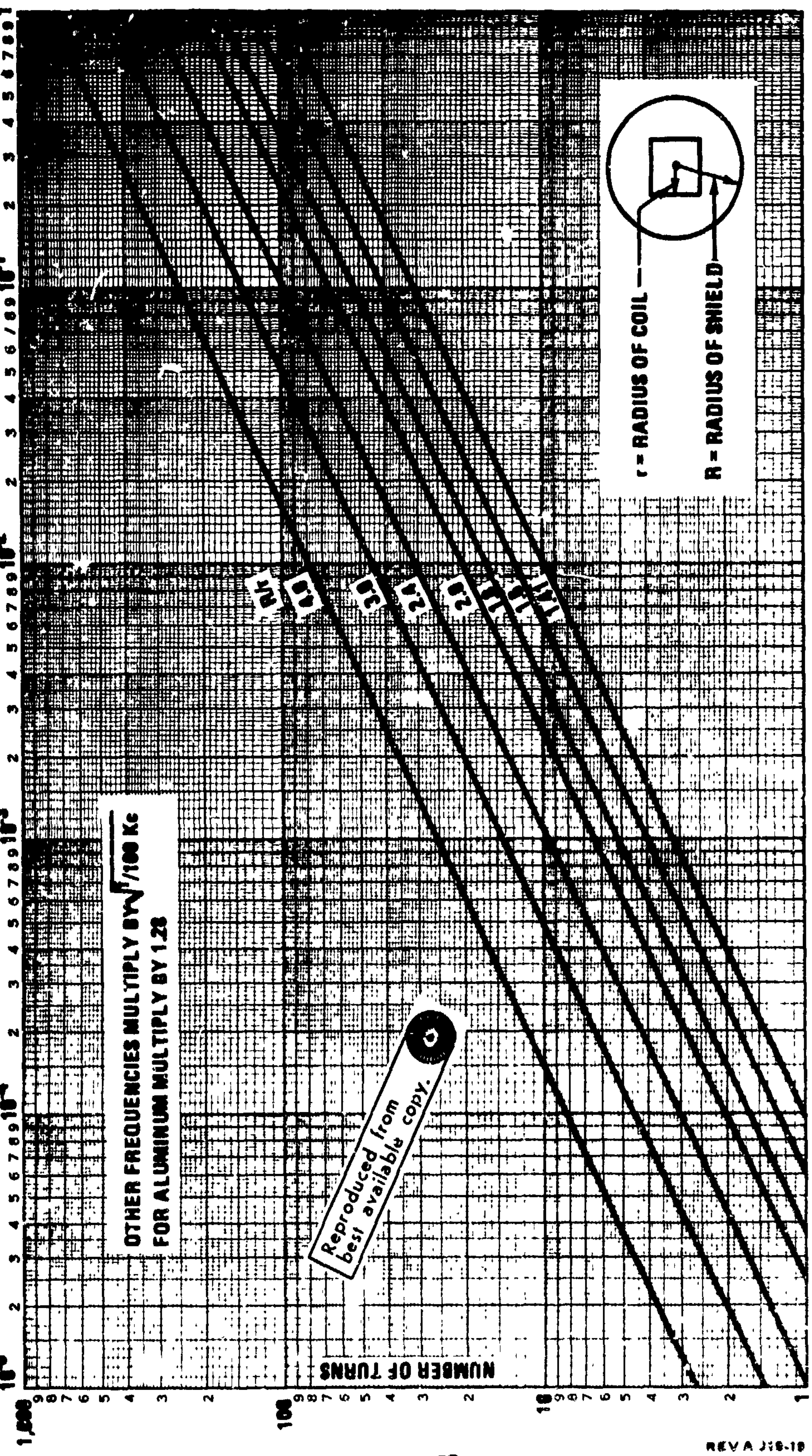

Figure 38. Shield Losses

SECTION IX

MODIFIED MODEL DESIGN

The conclusions from our inductor study were that the excessive losses in the tuning coils were due to self-parallel resonance since these coils had over 2000 ohms of reactance. It was necessary then to reconfigure the model to reduce the tuning coil reactance to less than 1500 ohms per element.

There are several methods for increasing the capacitance per element in the PARAN system.

1. The top hat area may be increased

2. The number of elements may be decreased

A combination of both of these alternatives may be the optimum approach.

The most direct method of increasing the capacity per element is to decrease the present four-element configuration to two elements. The reactance for each of the four elements was about 2400 ohms, and this will be 1200 ohms for each of two elements. A typical inductor would be a 48-inch diameter, 48 inches long with 110 turns of 1/4-inch tubing. This will be 10 millihenries and 1200 ohms reactance at 27 kHz. From Figure 37 the resistance of 1/4-inch tube is 1.2 ohms per 1000 feet, or 1.5 ohms for the 1250 feet required.

Figure 39 shows the circuit parameters with 1.5 ohms coil loss, 3.33 ohms ground loss at 27 kHz, and a radiation resistance of .0224 ohms. The efficiency of the system is equal to each of its elements and is

$$\eta = \frac{R_\alpha}{R_L \; T \; R_\alpha \; T \; R_g} = \frac{.0224}{1.5 + .0224 + 3.33} \qquad (50)$$

$$\eta = .00462 = .462\% \qquad (51)$$

This will meet the specification, but not the design goal. Tests were run on the present model as modified to confirm the above prediction. Two of the top hat connections were removed

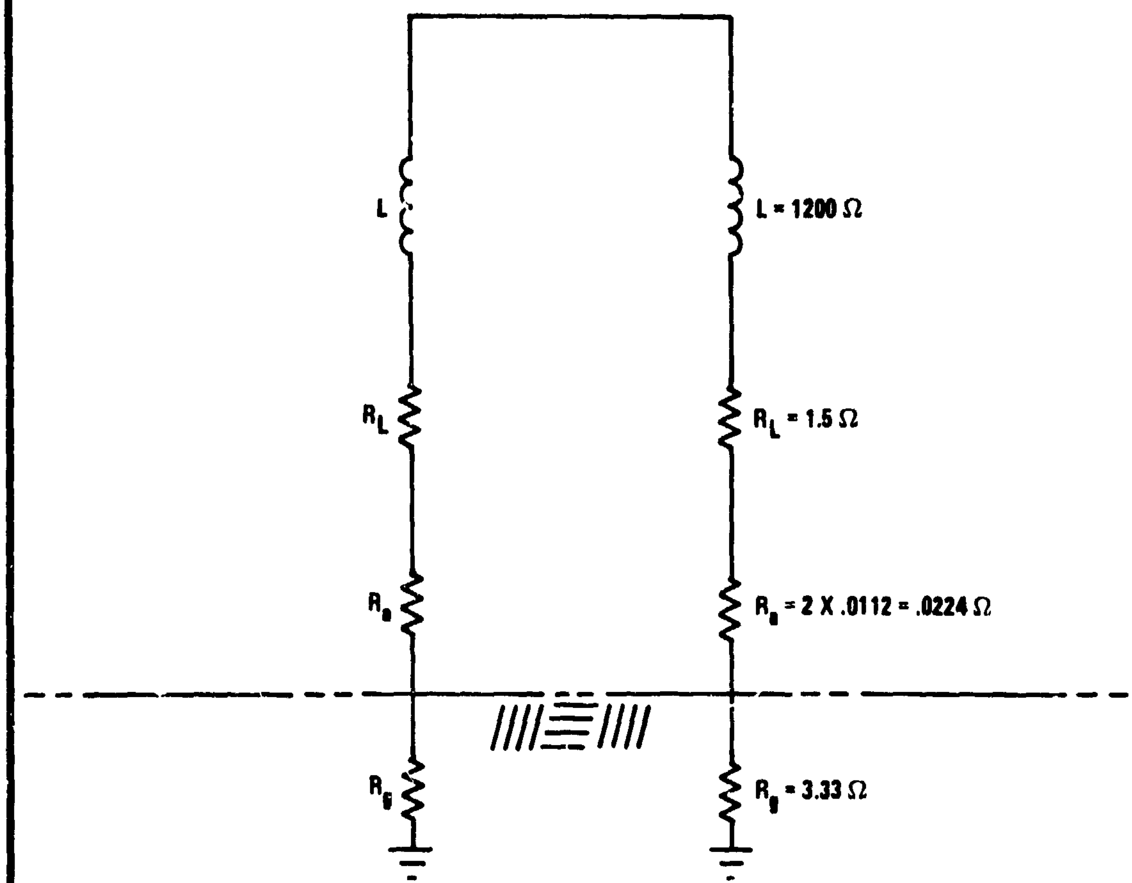

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Figure 39. Circuit Two Element PARAN Antenna

and the following measurements were made using the presently installed coils which were tapped down to produce resonance.

100 Watts Input

Measured Coil Reactance	1480 ohms
Measured Coil Resistance	3.1 ohms
Measured Coil Current	2.72 amps
Measured Base Current	2.3 amps
Measured Field Intensity	2.73 mV/m
Radiated Power	.215 watts
Measured Efficiency	.215%
Ground Resistance	5.5 ohms
Radiation Resistance	.0204 ohms
Top Hat Voltage	90 kV (50 kW)

correlating with predictions from Figure 39.

With a lower reactance top hat, the tower base currents and the coil currents have a smaller ratio as shown by the measurements. The coil resistance can be transferred to the tower base by the square of the current ratio to retain the power loss conditions.

$$R_{base} = R_{coil}\left(\frac{I_c}{I_{base}}\right)^2 = 3.1 \times \left(\frac{2.72}{2.2}\right)^2 \qquad (52)$$

$$R_{base} = 4.85 \text{ ohms} \qquad (53)$$

$$\eta = \frac{.0204}{4.85 + .0204 + 5.5} \times 100\% \qquad (54)$$

$$\eta = .218\% \text{ (approximately .215 as measured)} \qquad (55)$$

Therefore as previously shown, if the coil loss is 1.5 ohms and the ground loss is 3.33 ohms, the efficiency will be

$$\eta = \frac{.0204}{1.5 + .0204 + 3.33} \tag{56}$$

$$\eta = .42\% \tag{57}$$

By adding two supports and driving three elements as shown in Figure 40, the antenna can be made to meet the design goal of .5% efficiency. This antenna has approximately the same diameter as the diagonal of the previous four-element array and reduces the top hat reactance to 1000 ohms for each of the three tuned elements.

The predicted efficiency from Figure 41.

$$\eta = \frac{.0336}{1.5 + .0336 + 3.33} \times 100 = \% \tag{58}$$

$$\eta = .692\% \tag{59}$$

A model of this antenna was installed and measurements taken as follows:

<u>100 Watts Input</u>

Measured Coil Reactance	970 ohms
Measured Coil Resistance	3.0 ohms
Measured Coil Current	2.075 amps
Measured Base Current	1.9 amps
Measured Field Intensity	3.50 mV/m
Radiated Power	.354 watts
Measured Efficiency	.354%
Radiation Resistance	.0327 ohms
Ground Loss	5.62 ohms
Top Hat Voltage	45 kV (50 kW)

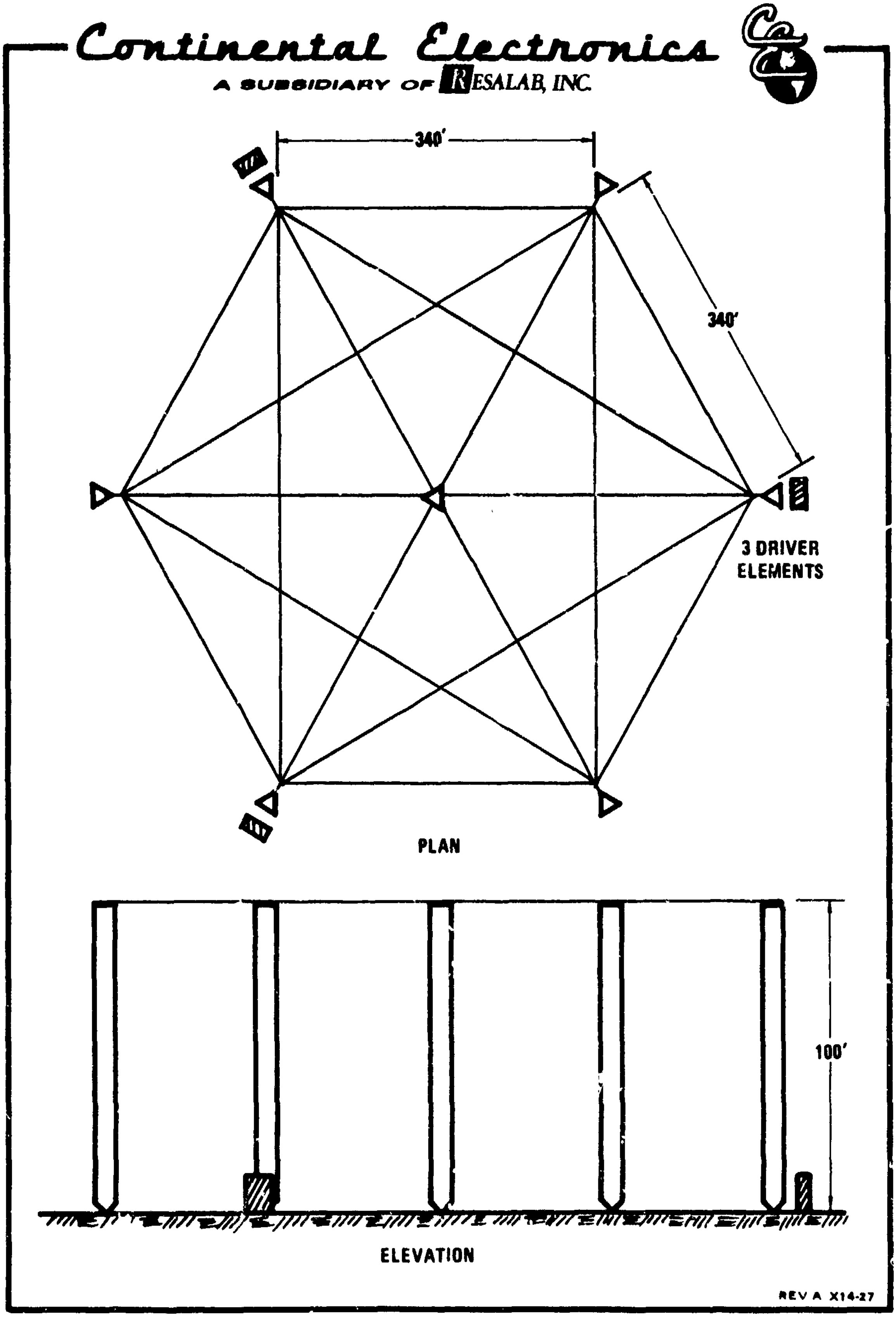

Figure 40. Three Element PARAN Antenna

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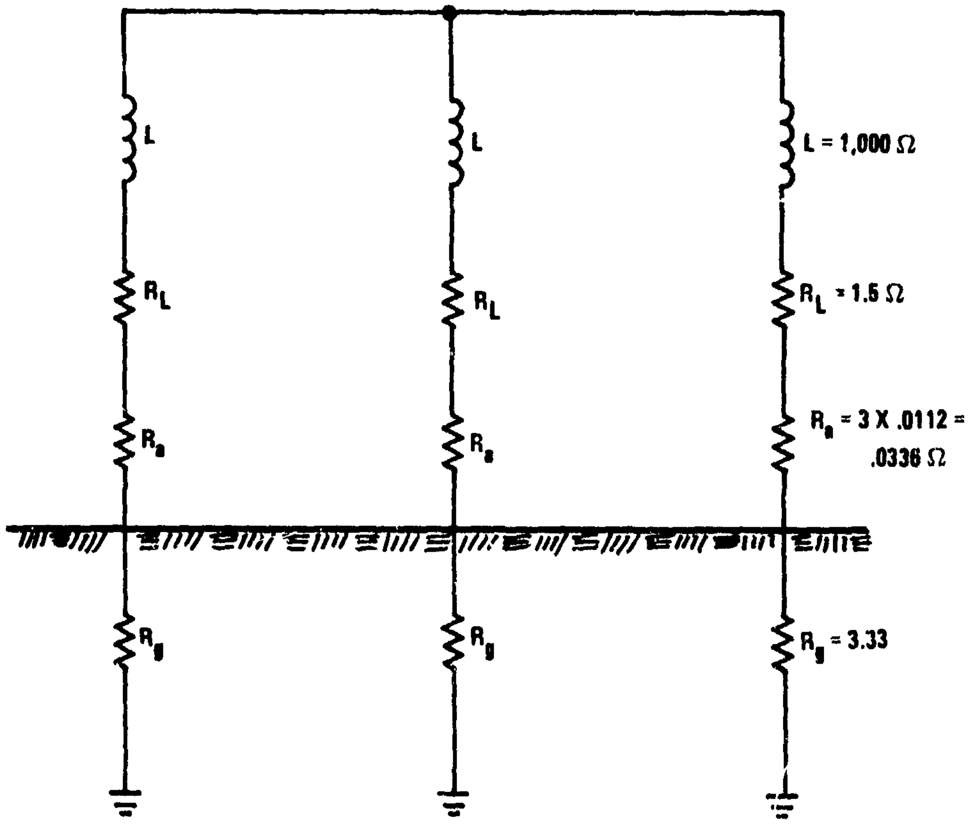

REV A X14-28

Figure 41. Circuit Three Element PARAN Antenna

Correlating with predictions from Figure 41, the equivalent coil loss at the antenna base is

$$R_{c_b} = \left(\frac{I_c}{I_b}\right)^2 R_c = \left(\frac{2.075}{1.9}\right)^2 x\ 3 \qquad (60)$$

$$R_{(\text{coil at base})} = 3.28 \text{ ohms} \qquad (61)$$

$$\eta = \frac{.0327}{3.28 + .0327 + 5.62} \qquad (62)$$

$$\eta = .365 \text{ (approximately .354\%)} \qquad (63)$$

Here again, if the coil loss is 1.5 ohms and the ground loss is 3.33 ohms, the efficiency will be

$$\eta = \frac{.0327}{1.5 + .0327 + 3.33} \times 100 \qquad (64)$$

$$\eta = .673\% \qquad (65)$$

As requested by RADC, field intensity measurements were extended to 40 miles on this model as shown in Figure 42.

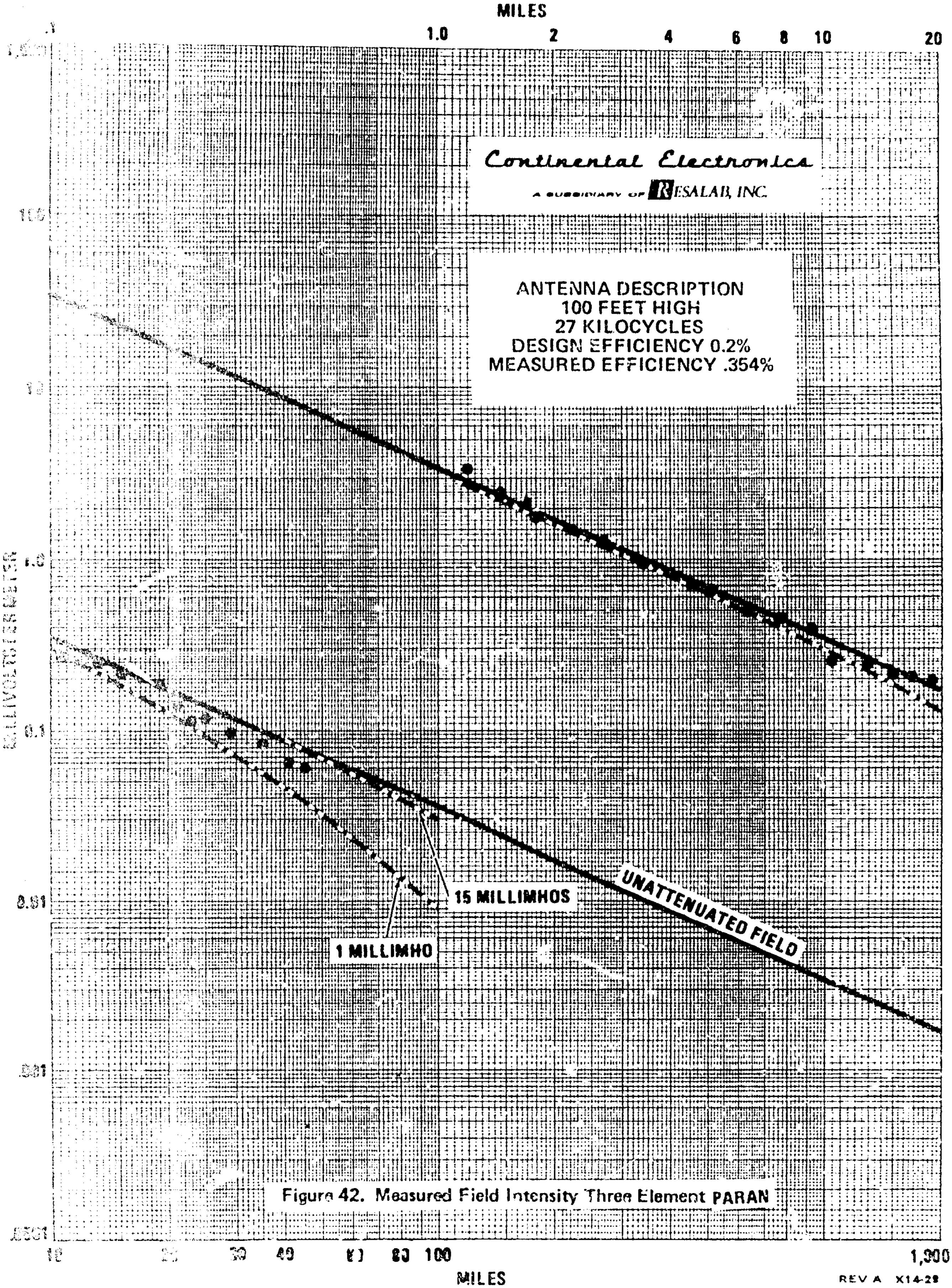

Figure 42. Measured Field Intensity Three Element PARAN

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

With the increased characteristic admittance of soil at 27 kHz, it appears that the 5.5 ohm ground resistance of the model will be close to the predicted 3.33 ohms using the present ground system. It appears that a reasonable coil size using 1/4-inch tubing will hold coil losses to 1.5 ohms at 27 kc. This can be further reduced with larger tubing or Litz wire.

During the last month's tests, the original top hat configuration was strapped together at the towers, thereby eliminating the angular current path for each element. There was no change in the resonant frequency of the antenna model. The reason for this change was to simplify the mechnical design and reduce structural loading. It appears that there is little or no effective series inductance in the special configuration and it can be eliminated for a more unified lacing of the top hat as shown on the three-element model of Figure 40.

The development work has now reached the point where two models have been developed and tested. One will more than meet the specified efficiency of 0.2% efficiency as obtained on the model and with proper design, the full scale model should exceed 0.4% efficiency. The other scale model has achieved 0.354% efficiency, and with proper design, should exceed the design goal of 0.5% efficiency for the full size model.

The final configuration should be capable of more than the 50 kilowatt input requirement and can be designed for at least 100 kilowatts. It is recommended that a full scale prototype be erected for the purpose of determining the upper limits on efficiency and power handling capability.

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13 ABSTRACT

The problem was the development of an antenna system no more than 100 feet high for the frequency range 27 to 60 kHz having a radiating efficiency of 0.2% with a design goal of 0.5%. The input power capability was to be 50 kW. A theoretical design was proposed with five support towers 100 feet high and a square area of 425 feet on a side. A model was constructed at a frequency scale of 6.66 to 1.0 for testing. The model achieved the 0.2% efficiency, but the major loss in the system was the tuning inductors. The inductor problem was studied and the conclusion was that inductors having more than 1500 ohms suffered unanticipated losses from circulating currents due to approaching self-resonance. This led to a reconfiguration of the original array to one having seven support towers in a hexagon 340 feet on a side. Measurements on the model indicated 0.350% efficiency with a predicted efficiency for the full size antenna of 0.673%. The modification reduced the voltage on the system to 45 kV for 50 kW and indicate that a design for 100 kW input power is feasible.

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